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STEVEN E. STRUKEL
MARK E. TILLMAN
DONALD R. BARR
JAMES E. ARMSTRONG

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This study attempts to answer the question of how to quantify the value of reconnaissance. We first examine the role of reconnaissance in the battle process, to include defining reconnaissance and conducting a task/mission analysis. Next, we explore a potential methodology for Army analysts to use in quantifying the value of new reconnaissance systems, doctrine, or force structures. Lastly, this paper chronicles several ongoing efforts to validate and refine this proposed methodology.



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United States Military Academy
West Point, New York 10996

# Quantifying the Value of Reconnaissance

Captain Steven E. Strukel
Donald R. Barr
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OPERATIONS RESEARCH CENTER
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Directed by
Lieutenant Colonel James E. Armstrong, Jr. Ph.D.
Director, Operations Research Center

Approved by
Colonel James L. Kays, Ph.D.
Professor and Head
Department of Systems Engineering

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# Executive Summary

Quantifying the war fighting value of reconnaissance is a hard problem. Standard analytical techniques fail to identify second and higher order effects of reconnaissance when integrated in a combat model. Additionally, current simulation techniques fail to model the human factor in information transfer and decision making. Finally, conventional measures of effectiveness concentrating on attrition (loss exchange ratios, killer/victim scoreboards, etc.) are clearly inadequate when tasked to measure reconnaissance effectiveness.

This study attempts to answer the question of how to quantify the value of reconnaissance. We first examine the role of reconnaissance in the battle process, to include defining reconnaissance and conducting a task/mission analysis. Next, we explore a potential methodology for Army analysts to use in quantifying the value of new reconnaissance systems, doctrine, or force structures. Lastly, this paper chronicles several ongoing efforts to validate and refine this proposed methodology.

The methodology proposed in this paper involves a three step process. First, a new or existing reconnaissance system should be examined using an *analytical model*. The analytical model is used to determine basic performance measures of a system prior to more costly/involved analysis, as well as assist in developing initial scenarios for a simple simulation involving the system(s) in question. Second, using a standard simulation tool (such as JANUS), the analyst conducts a *simple simulation* of a combat scenario involving the reconnaissance system. Data obtained from this simulation is used to refine the analytical model and the combat scenario. Finally, a *complex simulation* is conducted. The complex simulation should include "man-in-the-loop" decision making and information exchange to insure higher order effects are accurately modeled. Distributed interactive simulations (prototyped by SIMNET and AIRNET) are exemplary tools for the conduct of the complex simulation. With the appropriate data probes and measures of effectiveness, and an experimental design validated through the simple simulation, the results of the complex simulation should enable the analyst to quantify the value of reconnaissance.

# Quantifying the Value of Reconnaissance

> The ultimate purpose of acquiring, processing, communicating, and storing and retrieving data and information is to enable the decisionmaker to make and implement decisions. When the decisionmaker is a military commander, the more accurately and efficiently he can do this, the more time he has available to manipulate his control inputs (e.g., weapons and forces). This effectively broadens his options and increases his likelihood of success. (Hwang, et al., 1982, pp. 55)

## 1. Introduction

Although military commanders and historians have qualitatively championed the value of reconnaissance, very few research efforts have attempted to quantify the impact of reconnaissance on warfighting capabilities. Shrinking procurement and personnel resources combined with the shifting of Army focus towards regional, contingency-based operations are forcing us to consider carefully how we equip, fight, and structure the force. Without analytical techniques to quantify its value, the Army runs the risk of under (or over) resourcing scarce personnel and dollars to the reconnaissance mission. Similarly, development of appropriate warfighting doctrine to support contingency-based operations would be difficult without an accurate measuring stick for the value of reconnaissance. This paper outlines a methodology for understanding, measuring, and quantifying the value of reconnaissance.

### 1.1. Defining Reconnaissance

The working definition of reconnaissance used for this project was proposed by MG Robinson, CG of the U.S. Army Aviation Center:

> Reconnaissance forces must be capable of gaining insights on the physical capabilities, intent, and will of current and future threats across the spectrum of contigency based operations, and deny the enemy's ability to gather this information.

An argument exists that this is the definition of reconnaissance and security, not just reconnaissance. This highlights the dichotomy between close and deep reconnaissance. Doctrinally, deep reconnaissance is tasked to strip away enemy reconnaissance assets, identify high value targets for destruction (for example, SCUD launchers in Desert Storm), and gather information on capabilities, intent, and will. Close reconnaissance is then primarily responsible for locating specific enemies in a commander's area of interest, where engagement of enemy reconnaissance forces or high value targets is much more likely to result in the loss of friendly recon assets. Aggregation of these tasks over the

depth of the battlefield reveals a common, underlying purpose of reconnaissance; reduction of uncertainty about the battle for the friendly commander while increasing the enemy commander's uncertainty.

To better understand reconnaissance, we have partitioned the warfighting process into three discrete and sequential stages as shown in Figure 1.1. The purpose of the first stage, reconnaissance, is to gain information about the enemy force in terms of location, capabilities, intent, and will. Concurrently, attempts are made to deny this information to the adversary by conducting counter-reconnaissance. Reconnaissance elements communicate (ideally) all the information obtained for use in the next stage: Command-and-Control (C2).

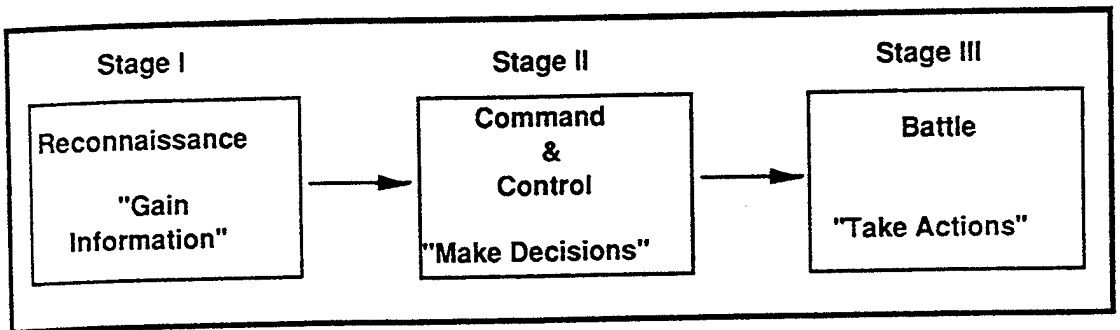


Figure 1.1. Warfighting Process

The purpose of the C2 stage is to support and communicate decisions. These decisions focus on setting terms for the next stage, battle, so that friendly forces have the highest possible chances for the best outcome (as defined by the unit's mission). We normally want to achieve our objectives quickly and at the lowest possible cost in terms of personnel, systems, and/or terrain losses.

The actual battle where the information and decisions of the earlier stages are implemented is the last stage of our conceptual model. Correct decisions based on accurate and timely intelligence gives us the ability to position our forces and target fires so we achieve the effects of mass. Failure in either of the information gathering or C2 stages can result in a subsequent failure to concentrate forces and fires at the critical point(s) of the battle.

We recognize that warfighting doesn't occur in separate, sequential stages. The three stages as depicted overlap in a continuous "information-decision-action" cycle, however, as a conceptual framework, we will treat each stage as a discrete event in the cycle.

Additionally, a commander's emphasis on reconnaissance will certainly vary based on the mission, enemy, terrain, troops available, and time (METT-T) as well as the commander's depth of responsiblity. A battalion commander fighting a doctrinal battle (with brigade, division, and corps assets deployed forward of his positions) may have little interest in fighting the counter-recon battle. He can expect the covering forces to strip enemy reconnaissance and his primary uncertainties about the battle might then be which avenue(s) the enemy will use to enter his sector. Similarly, the Corps Commander fighting this same battle may be uncertain regarding the location of key enemy assets, such as

Theater Ballistic Missles (TBM) and logistics sites and concentrate his reconnaissance assets accordingly. The common thread between METT-T and level of reconnaissance is that it is used by the commander and his staff to reduce uncertainty about the battlefield and increase friendly situation awareness.

## 1.2. Quantifying Reconnaissance

It is readily apparent why quantifying the effects of reconnaissance is such a difficult task (see Figure 1.2 Nature of Reconnaissance). Reconnaissance does not occur in a vacuum. The staff filters information, with the potential of introducing errors and delays. Commanders may or may not make good use of the information provided. Even with excellent information poor decisions may be made, likewise, correct decisions regarding deployment of forces and fires may occur with poor or misleading data. Finally, the outcome of a battle is prone to chance events. For example, a single "killer" tank crew can drastically alter the course of a task force fight, as can a random communications failure at a critical point in the battle.

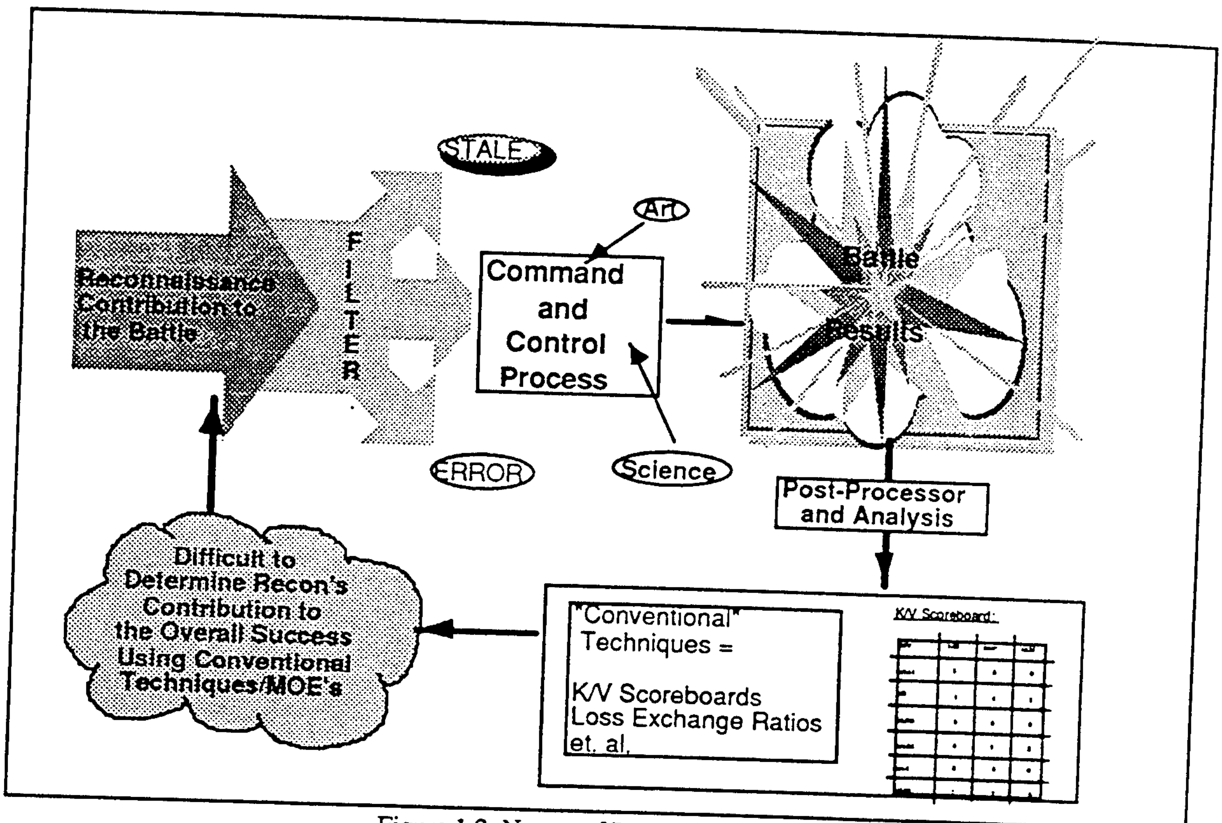


Figure 1.2. Nature of Reconnaissance

A simple way of describing the effects of reconnaissance is to state that a commander selects his course of action based on information provided through reconnaissance (from all sources) of the enemy's capabilities, intent, and will. In the long run, the quality and timeliness of information will dictate how effective the commander can expect to be in making this selection. Constructive simulations (VIC, Eagle, CORBAN, etc.) used by

Army analytical agencies are geared to fight only one battle (which we will call the end state battle--the battle fought after both enemy and friendly commanders have "selected" their courses of action). Constructive simulations, by their very nature, are therefore incapable of reproducing the major effects of reconnaissance: shaping the commander's picture of the battle.

The question then remains, how do we quantify the effects of reconnaissance given the various filters, decisions, and random events that contribute to force effectiveness? One potential methodology to answer this question is to determine the correlation (if any) between measures of information and measures of force effectiveness. The first step in this methodology is to determine what measures are of interest; what tasks does reconnaissance perform and how do they influence the outcome of the battle? Next, we must design an experiment that efficiently models the war fighting process and will quantify our measures of interest. Finally, we must conduct our experiment and analyze the results for evidence of a positive correlation between reconnaissance and battle outcome. By conducting such experiments over a range of potential scenarios, we can quantify the value of reconnaissance in terms of friendly and enemy losses, terrain objectives held or lost, etc..

## 1.3. A Proposed Methodology

The method investigated in this paper for determining the value of reconnaissance consists of three steps:

1. Develop an Analytical Model. For any new reconnaissance systems, tactics, or missions, we should first conduct a "back-of-the-envelope" analysis. Here we estimate how known system parameters or dynamics will effect information gathering and combat performance. Of particular interest at this stage is analyzing the "pure" reconnaissance influence on combat results without second order effects (we isolate the results from the "filter" of the $C^2$ process).

2. Conduct A Simple Experiment. Armed with insights from the analytical model, we design experiments to support inferences concerning information and combat results. Stochastic simulations, such as Janus, are useful tools in this process. They allow us to investigate the estimates made in our analytical model between system parameters, information gathering capabilities, and combat performance.

3. Conduct Man-in-the-Loop Experiments. As previously stated, a successful battle is dependent on many factors. Exclusion of these factors in evaluating reconnaissance is highly undesirable. We lose the ability to examine the overall system dynamics, where these higher order effects have significant impact on combat performance. An emerging technology, Distributed Interactive Simulation (DIS), may be the key to effectively evaluating reconnaissance. Human factors within the filtering process are not lost in DIS and with the correct experiment, we will be able to evaluate the interactions between recon system parameters, information measures, and force effectiveness. Thus, we can quantify the value of reconnaissance in terms of system parameters linked to changes in force effectiveness.The flowchart at Figure 1.3. shows how these steps interact to determine the value of reconnaissance.

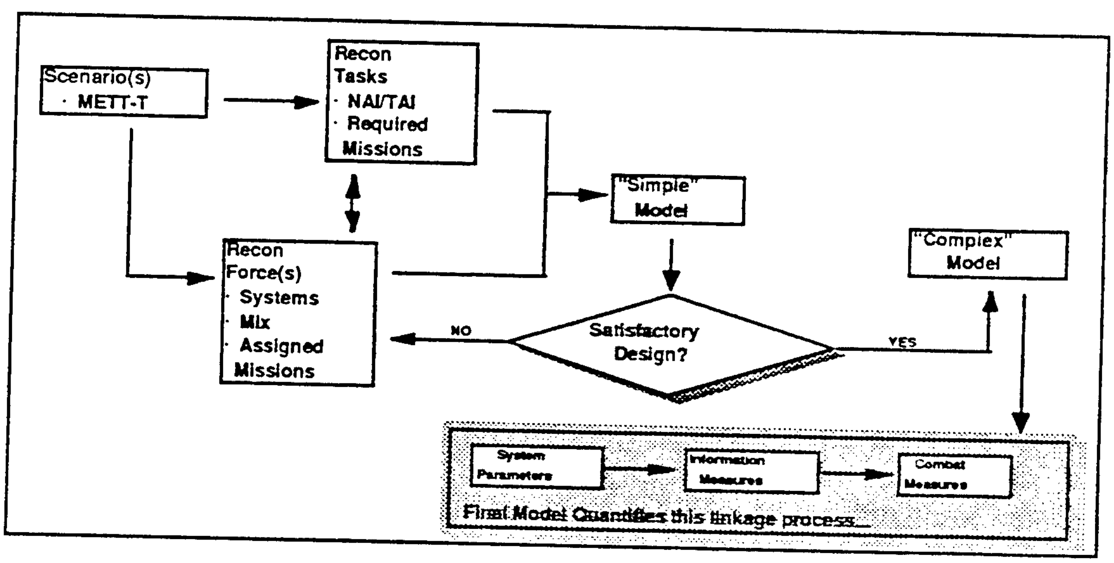


Figure 1.3. Flowchart for Quantifying the Value of Reconnaissance

# 2. An Analytical Model

Analytical models can be used to estimate a reconnaissance system's impact on force effectiveness. Examination of known (or projected) system parameters under the constraints of any given scenario (METT-T considerations) using analytical tools can indicate general levels of performance for measures of interest (from detection rates to estimates of losses). The specific analytical tool(s) to be used in a study is dependent on several factors; the level of detail required or desired in the study, available system information, availability of analytical tools, and preference of the analyst. The tool used in this study is a simple application of task analysis. Other, more rigorous tools are discussed at the end of this chapter. In addition, we examine some heuristic approaches and reconnaissance axioms discovered during our research.

## 2.1. The Role of Reconnaissance

The development of an analytical model requires that we first examine what commanders expect from their reconnaissance forces. From our definition of reconnaissance, we know that this role centers around reducing the commander's uncertainty about the battlefield and increasing the enemy's uncertainty. At this point, we introduce a new measure of effectiveness, entropy. Entropy is a measure of randomness (or uncertainty) present in a system. A more detailed explanation of the information measure "entropy" is found at Appendix A. As defined, we are interested in increasing the entropy of the battlefield as viewed by the enemy commander and decreasing the entropy as seen by the friendly commander. Reconnaissance affects the entropy level of friendly and enemy commanders through three activities:

1. Destruction of enemy reconnaissance assets. This reduces the amount of information gathering assets available to the enemy commander and should increase his entropy.

2. Disruption of enemy Command and Control. Through either active or passive measures, reconnaissance assets are useful in disrupting the enemy's capability to process and decide on information. Active measures include detection and targeting of enemy C2 nodes while passive measures are those associated with deception missions (ie. ruse, feint, demonstrations, etc.). Disruption of enemy C2 again increases the enemy's entropy since information available is not as effiecently processed or is in error (as successful deception operations will give the enemy commander a false picture of the battlefield).

3. Detection of enemy forces. This activity reduces friendly entropy through information gathering. The value of a target in a given scenario will dictate the amount of entropy reduced. For example, a Theater Ballistic Missle (TBM) launcher is of considerable more interest to the commander than the location of a Mess Kit Repair Company. Integral to detection of enemy forces is the ability to target high value enemy battlefield operating systems (such as a TBM launcher). This type reconnaissance is part

of the Hunter/Killer process. Reconnaissance systems with built-in weaponry increase responsiveness and flexibility in this type mission, no longer relying upon external killer systems (e.g. ATACMS, MLRS, Army or Air Force aviation).

Continuing with this "Top-Down" system design (as shown in Figure 2.1.), we subsequently identify the six missions (classical cavalry missions), 14 tasks and various systems available to acomplish these tasks that build into the value of reconnaissance. Finally, we see that these systems are in effect the aggregation of parameters (speed, detection capabilities, armor protection, radar and optical signatures, etc.) that when known, can be used to predict task (and therefore mission) performance.

By identifying the reconnaissance missions and tasks we have taken the first step in constructing a simple analytical model of reconnaissance. We must now conduct a more detailed task analysis to further develop this model into a usable product for predicting system performance.

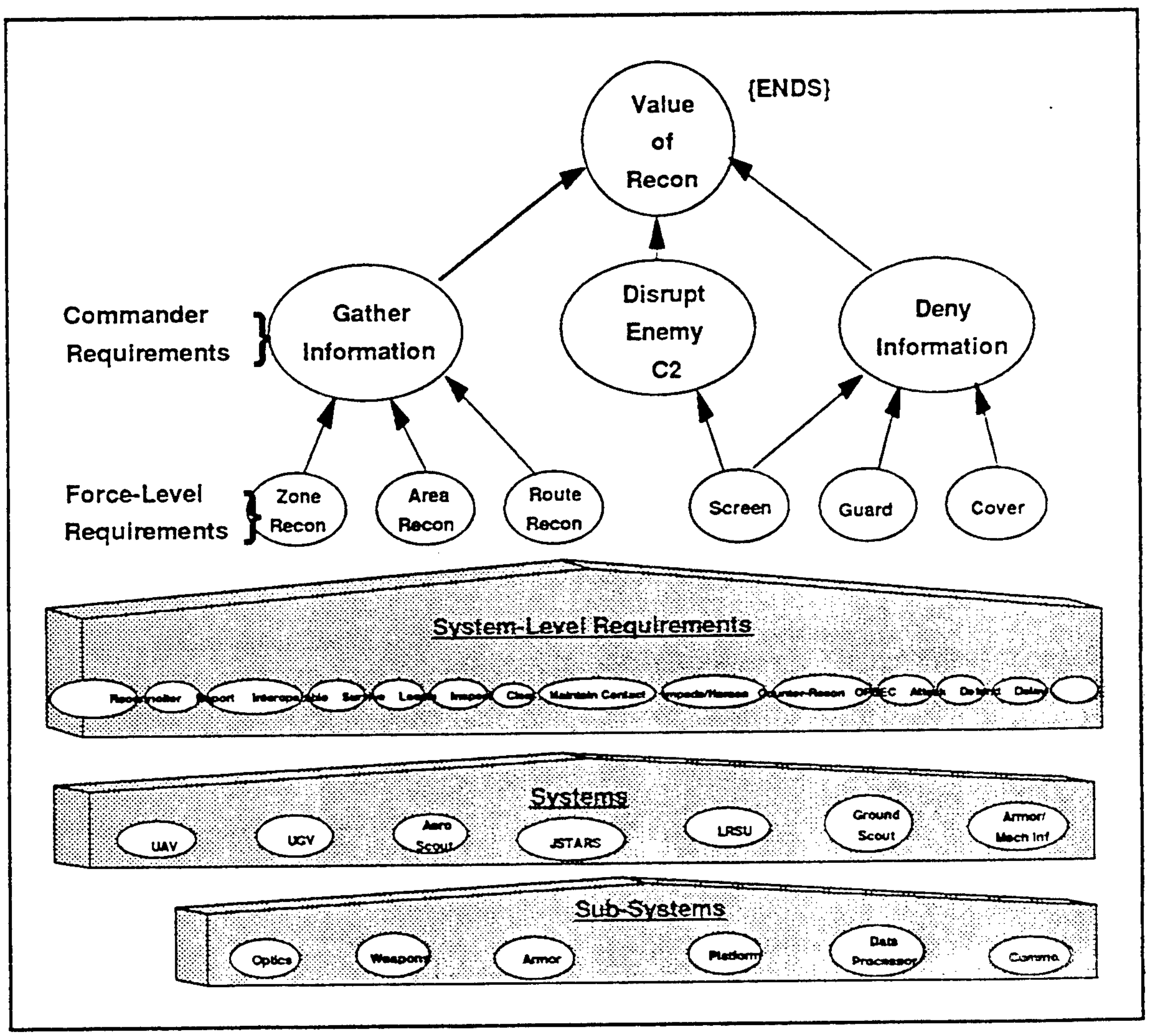


Figure 2.1. Value of Reconnaissance

## 2.2. Task Analysis

The goal of the task analysis is to gain an understanding of reconnaissance duties on the battlefield and then evaluate the general capabilities of different reconnaissance systems in conducting these duties. At Table 2.1, we have identified the six missions typically assigned to forces in a reconnaissance role as well as the 14 tasks that are associated with these missions. Although the hierarchy and descriptions of the missions and tasks presented are open to debate, the basic concept conforms to both the Armor and Aviation Centers' views on reconnaissance[1].

| | Cavalry Missions and Tasks | Zone Recon | Area Recon | Route Recon | Screen | Guard | Cover |
|---|---|---|---|---|---|---|---|
| (a) | Reconnoiter | x | x | x | x | x | x |
| (b) | Report | x | x | x | x | x | x |
| (c) | Interoperable | x | x | x | x | x | x |
| (d) | Survive | x | x | x | x | x | x |
| (e) | Locate | x | x | x | x | x | x |
| (f) | Inspect | x | x | x | | | |
| (g) | Clear | x | x | x | | | |
| (h) | Maintain Contact | | | | x | x | x |
| (i) | Impede/Harass | | | | x | x | x |
| (j) | Counter-Recon | | | | x | x | x |
| (k) | OPSEC | | | | x | x | x |
| (l) | Attack | | | | | x | x |
| (m) | Defend | | | | | x | x |
| (n) | Delay | | | | | x | x |
| | Total Tasks per Each Mission | 7 | 7 | 7 | 9 | 12 | 12 |

"x" indicates a task is required in conduct of the indicated mission

Table 2.1. Mission/Task List

The Mission/Task List also highlights the emphasis in the strictly recon missions on information gathering, while the security missions (Screen, Guard, and Cover) require close combat capability as well (although as previously noted, an unarmed recon system working as part of a dedicated hunter/killer team may prove capable of some of these tasks). Regardless of mission, however, it is apparent that a reconnaissance force (of one or more systems) will have to be multi-task capable to perform all of the anticipated tasks.

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1 The Armor Center would include Attack, Defend, and Delay on the mission list as part of the Economy of Force role often delegated to ground reconnaissance forces (ie., Cavalry). These are identified as tasks for the more security related missions of Screen, Guard, and Cover.

| | Task Performance Analysis | Aero Scout | Atk Helo | RAH | UAV | Ground Scout | LRSU | Armor | Inf (Mech) | C/B Radar | GSR | SLAR | JSTAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) | Reconnoiter | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| (b) | Locate | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| (c) | Report | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 1 |
| (d) | Interoperable | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| (e) | Survive | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 0 | 0 | 0 | 2 |
| (f) | Inspect | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| (g) | Clear | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| (h) | Maintain Contact | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 2 |
| (i) | Impede/Harass | 0 | 2 | 2 | 0 | 1 | 0 | 2 | 1 | 1 | 0 | 0 | 0 |
| (j) | Counter-Recon | 0 | 2 | 2 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| (k) | OPSEC | 1 | 2 | 2 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| (l) | Attack | 0 | 1 | 1 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 0 |
| (m) | Defend | 0 | 2 | 2 | 0 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 |
| (n) | Delay | 0 | 2 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 0 |
| | Performance Totals: Without Weightings | 10 | 18 | 21 | 8 | 17 | 6 | 17 | 15 | 4 | 4 | 4 | 6 |

Table 2.2. System/Task Performance

In Table 2.2, we extend this analysis with a very low resolution examination of the capabilities of various system often placed in a reconnaissance role. A system received a "2" (superior rating) if it excels at a particular task. A "1" (adequate rating) is earned if a system can perform that task, while a "0" is assigned to systems either physically incapable or doctrinally prohibited from performing a certain task (or has poor performance or high vulnerability when conducting the task). For example, Aero Scouts can certainly land to inspect a bridge for trafficability, but are strongly discouraged from doing so, while radar systems, such as JSTARS, are incapable of performing such tasks. These ratings <u>do not</u> reflect any of the METT-T factors that we know heavily influence the reconnaissance battle. Given a scenario with specific METT-T information and known responsibilities (depth of the battle, flank and rear security, covering forces, etc.), the analyst would want to "rescore" the system types. In particular, we would want to consider weather effects on flight operations and optical/ thermal performance, amount of area (and its terrain) to be reconnoitered, etc.. In the overall performance points awarded to systems, the analyst must also consider the specific tasks to be conducted for the assigned mission and the potential effects of <u>weighting</u> certain tasks. For example, if preservation of the force is critical in a scenario, then weighting the survival task can reflect this.

| Cavalry Missions and Systems | Zone Recon PERFORMANCE POINTS | Area Recon PERFORMANCE POINTS | Route Recon PERFORMANCE POINTS | Screen PERFORMANCE POINTS | Guard PERFORMANCE POINTS | Cover PERFORMANCE POINTS |
|---|---|---|---|---|---|---|
| Aero Scout | 8 | 8 | 8 | 10 | 10 | 10 |
| Atk Helo | 6 | 6 | 6 | 13 | 18 | 18 |
| RAH | 8 | 8 | 8 | 16 | 21 | 21 |
| UAV | 7 | 7 | 7 | 8 | 8 | 8 |
| Ground Scout | 9 | 9 | 9 | 10 | 13 | 13 |
| LRSU | 6 | 6 | 6 | 4 | 4 | 4 |
| Armor | 6 | 6 | 6 | 11 | 17 | 17 |
| Infantry (Mech) | 7 | 7 | 7 | 9 | 13 | 13 |
| C/B Radar | 3 | 3 | 3 | 4 | 4 | 4 |
| GSR | 3 | 3 | 3 | 4 | 4 | 4 |
| SLAR | 2 | 2 | 2 | 4 | 4 | 4 |
| JSTAR | 4 | 4 | 4 | 6 | 6 | 6 |

Table 2.3. System/Mission Performance

In Table 2.3 above, we have aggregated the performance points over the tasks in a mission for each system. Note that multi-purpose systems capable of performing many tasks score quite well while "one-dimensional" assets (such as radar) do rather poorly. Again, a reminder that these estimates are made independent of METT-T factors; ground scouts *in general* perform reconnaissance quite well, however on a cross-FLOT (into enemy terrain) mission to hunt for TBMs, ground scouts would be totally unsuitable due to slow responsiveness, vulnerability, need for resupply, large signature, etc.. Whatever analytical model is used to design a reconnaissance force, METT-T (derived from the scenario) must be a significant consideration.

## 2.3. Reconnaissance Heuristics and Axioms

Throughout this research effort, we have found general agreement on many "underlying truths" regarding reconnaissance. These translate into "rules of thumb" to assist the analyst in constructing an analytical model.

### 2.3.1. Why Develop an Analytical Reconnaissance Force

Army analysis of reconnaissance is usually prompted by the acquisition process associated with a new system (for example, the Future Scout Vehicle or the RAH-66 Comanche), proposed restructuring of the force (Brigade Reconnaissance and Security Element Analysis), or changes in doctrine. In any case, the question is not "What is the Value of this reconnaissance system?", but instead the analyst must ask "What is the Value of this reconnaissance sytem given a realistic scenario with known METT-T factors?" As stated previously, reconnaissance does not occur in a vacuum. Based on the scenario; the enemy's ability to destroy or disrupt our recon systems will vary, the types and quantity of killer systems supporting the reconnaissance "hunters" will differ, and the relative importance of finding the enemy will change based on force ratios. For example, if Blue has an overwhelming superiority over Red, the relative value of reconnaissance is reduced. The value of recon ("active" information gathering) is directly related to the "penalties"

associated with relying instead upon "passive" information gathering (as the main body drives straight into the ambush for example).

The analytical model, then, is intended to answer the question of what reconnaissance (and supporting killer) systems should be included in the experiment, given a scenario and known METT-T.

### 2.3.2. Force Considerations

As seen in the Task Performance analysis, system capabilities and strengths differ significantly, particularly between air/ground platforms and radar/optical sensors. Some of the underlying differences in systems capabilities include:

- **Granularity.** Radar systems in particular provide a low resolution picture of the battlefield. For example, JSTARS gives the commander "red dots" which may or may not be enemy vehicles. This type of information, combined with doctrinal and situational templates for enemy locations, is valuable in "queuing" higher resolution recon assets. Additionally, this information will show the commander where the enemy is probably not located. Based on the scenario, this may result in significant reduction of uncertainty for the commander and increase the efficiency of other reconnaissance assets (i.e., the enemy is NOT at Named Area of Interest (NAI) 1 or 2 based on the JSTARS data, however, NAI3 is crawling with red symbols, so send the scout helicopters to investigate...).

- **Timeliness.** Platform responsiveness and data processes have direct impact on the timeliness of information. A common complaint during Desert Storm was the fusion delay prior to receiving JSTARS information. This highlights both the need for a methodology such as the one we are describing (to study reconnaissance systems) and the issue of timeliness. Aerial platforms, while incapable of performing ALL the tasks of ground reconnaissance, are still quite valuable given their ability to "sprint" from NAI to NAI.[2]

- **Accuracy.** This is another piece in determining the quality of a reconnaissance systems information. Accuracy is an aggregation of a systems detection probabilities (detect or fail to detect a target) and false alarm rate ("seeing" a taget that is not there). Systems such as radar may have excellent detection probabilities, but depending on the scenario may also have high false alarm rates (in SWA, JSTARS had only occaissional difficulty separating the camels from Iraqi units; in a Bosnia or Korea, however, separating false alarms from enemy activities would prove a much

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[2]Although this is a study in reconnaissance, it is worthwhile to note that the Army is expending considerable effort on the issue of timeliness. From Horizontal Integration (linking hunters to killers) to Vertical Integration (data transfer between echelons of headquarters), the Army is interested in reducing fusion and data transfer times through automation, digital communications, and development of artifical intelligence.

more difficult task, given the large civil population and urbanization). Intuitively, as a platform's rate (or area) of coverage increases, its accuracy will decrease. Similar sensors mounted on ground and aerial platforms may show drastic variances in accuracy (dependent on terrain and weather, primarily).

### 2.3.3. Simulation Development

A high resolution analytical model (beyond our simple task/ performance analysis), using detection rates and lethality measures, will enable the analyst to better predict force performance, before expending any resources. The results of the analyst's initial work with an analytical model can then be used to design simple experiments and serve as a "reality check" when results are obtained from simulation.

Experimental design considerations include development of the forces to be examined in the simple experiment such that they provide overlapping capabilities using multiple sensors and platforms, along with consideration of the mission, enemy, terrain, etc.. We also want to account for hunter/killer capabilities (for example, to cause equivalent losses to the enemy, an RAH-66 Commanche equipped force should need fewer artillery assets in support than an Unarmed/Unmanned Aerial Vehicle). Other considerations include how often does the recon system need to look at a given piece of terrain? (Based on threat mobility and battlefield dynamics, what should the recon frequency be?) What can we simulate? (In both the stochastic and interactive simulation, what is feasible? What do we assume?).

## 2.4. Extensions and Future Work

One promising avenue of research into analytical models of reconnaissance is based on Lanchester equations. This may provide a "stand-alone" model for computing the value of reconnaissance, utilizing the differences in aimed and area fire (square law versus linear law models). Additional information regarding the Lanchester reconnaissance model is located in the next chapter.

Additionally, work continues on developing an analytical model that will facilitate computing the amount of reduction in entropy a system or group of systems should contribute. If we are successful in computing entropy (a single measure of reconnaissance effectiveness), then eventual response surface analysis will be possible (from the input of system parameters yielding estimates of combat effectiveness). The analytical models and results to date regarding the use of entropy in reconnaissance evaluations is also presented in the next chapter.

Finally, we plan to continue to refine the task/performance analytical model, with possible extensions to include a linear programming solver using METT-T constraints and input of key system parameters.

# 3. Experimental Results

To support our investigation of our proposed three step methodology, a number of studies have been initiated through the Operations Research Center, United States Military Academy. Four of these efforts are examined in this paper as follows:

- The Value of Reconnaissance: The Lanchester Analytical Model. This ongoing study examines the use of Lanchester equations in developing an analytical model of reconnaissance. Examination of empirical evidence may provide a method for estimating parameters in attrition models corresponding to reconnaissance effectiveness. Follow on experiments using the Janus simulation tool and study of historical data will provide a first look validation for this modeling technique.

- Evaluating Reconnaissance: A Contingency Scenario with Competing Systems. This was a detailed cadet design team study of two potential reconnaissance systems in a contingency scenario. Individual research prior to scenario design concentrated on recon and combined arms tactics, warfare in Bosnia/Hercegovina (the location of our hypothetical scenario), and design methodology. The scenario examined recon system capabilities in locating an enemy's "center of mass" with man-in-the-loop decisions regarding force allocations based on the recon information. Traditional measures were then used to evaluate the performance of the two recon systems in this scenario.

- Using Entropy to Measure Recon Value: An Experiment in Alternative Measures of Effectiveness. This was our first effort at examining a new measure of reconnaissance effectiveness, entropy. Decreases in entropy (the level of randomness or uncertainty) in a system should correspond to the effectiveness of reconnaissance. A small JANUS experiment was conducted using two different recon systems (in this case UAV and a light Reconnaissance/Attack Helicopter[3]) sent on search patterns against 50 stationary, nonfiring threat targets. Area searched and targets found contributed to the reduction of entropy. Method and results are discussed.

- Extensions in Reconnaissance: A Study in Measures and Design. A more involved study of entropy and experimental design considerations. Entropy extensions include target value in reconnaissance (Hi/Lo mix of enemy forces), "operationalizing" the entropy measure (development of the appropriate data probes and computational aids to automate the calculation of entropy values during a simulation with multiple recon assets and lethal targets), and examination of hunter/killer relationships. While still in progress, the scenario and some of the initial results of this study are discussed.

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[3]Note that throughout the discussion of ORCEN experimental results, any reference to the Comanche or RAH-66 should be considered as an unspecified light Reconnaissance/Attack Helicopter (RAH). In our JANUS simulations, we were concerned primarily with methodology (could we actually evaluate reconnaissance). To this end, we conducted numerous experiments using UAV and RAH platforms. Specifications for these platforms cannot be considered accurate models of any proposed or existing systems (we were modelling the concepts of UAV's and RAH's).

# 3.1. The Value of Reconnaissance: The Lanchester Analytical Model

## 3.1.1. Purpose

The primary goal of this study is to provide an analytical tool which, given a particular reconnaissance system, would provide a quantitative measure as to its value. For example, the worth of a recon system is determined by the impact the use of this system would have on the outcome of a battle. The results may show for instance that by employing this recon system, the size of the force needed to achieve victory is reduced by 30%. Well informed and justified decisions may be the result of such an analysis. Additionally, this study will validate the analytical model through the use of the JANUS computer combat simulation. The results of battles run on the Janus system are compared with the predicted results from the analytical models. Similar results from both methods lend credence to the Lanchester models used.

## 3.1.2. Reconnaissance

In essence, reconnaissance and the information it provides allows a force to achieve aimed fire on the enemy. The Lanchester equations will be used to model scenarios in which the information gained allows one of the forces to transition from *area to aimed fire. Similarly, effective counter reconnaissance measures can deny, or inhibit the enemy's ability to make this same transition. The information gained from reconnaissance can be thought of as a reward which increases the rate of transition from area to aimed fire. This in essence allows the force to mass its fires, as opposed to massing its forces. The goal from the Blue forces perspective, would be to transition as quickly as possible, while at the same time forcing their opponent to transition very slowly.*

## 3.1.3. General

Lanchester equations have been used extensively to model a two sided conflict in order to predict the outcome of a battle. Originally Lanchester used his difference equations to quantitatively demonstrate the great advantage of concentrating forces. The application of his theory produced several models which were shown to effectively simulate various scenarios of modern warfare. Table 3.1 below shows some models in which Lanchester Models have been used.

| Lanchester Law | Model |
|---|---|
| Linear Law | Area fire -vs- Area fire |
| Square Law | Aimed fire -vs- Aimed fire |
| Mixed Law | Area fire -vs- Aimed fire |
| Shaffer's Model | Transition from Area to Aimed fire -vs- Area fire |

Table 3.1. Lanchester Laws

### 3.1.4. Key Lanchester Equations

**Linear Law (both sides using area fire)**

| | |
|---|---|
| $\frac{\Delta B}{\Delta t} = -\alpha_R BR$ | Rate of change of Blue w.r.t time |
| $\frac{\Delta R}{\Delta t} = -\alpha_B RB$ | Rate of change of Red w.r.t. time |
| $\alpha_B = p_B(h) \bullet p_B(k \mid h) \bullet r_B$ | Rate at which Blue attrites Red w/ area fire |
| $\alpha_R = p_R(h) \bullet p_R(k \mid h) \bullet r_R$ | Rate at which Red attrites Blue w/ area fire |
| $B_{i+1} = B_i - \alpha_R B_i R_i$ | DDS describing Blue force size in time period *i+1* |
| $R_{i+1} = R_i - \alpha_B R_i B_i$ | DDS describing Red force size in time period *i+1* |
| $\alpha_B B_0 > \alpha_R R_0$ | Blue wins if this inequality holds |

**Square Law (both sides using aimed fire)**

| | |
|---|---|
| $\frac{\Delta B}{\Delta t} = -\beta_R R$ | Rate of change of Blue w.r.t time |
| $\frac{\Delta R}{\Delta t} = -\beta_B B$ | Rate of change of Red w.r.t. time |
| $\beta_B = \hat{p}_B(h) \bullet \hat{p}_B(k \mid h) \bullet \hat{r}_B$ | Rate at which Blue attrites Red w/ aimed fire |
| $\beta_R \hat{=} \hat{p}_R(h) \bullet \hat{p}_R(k \mid h) \bullet \hat{r}_R$ | Rate at which Red attrites Blue w/ aimed fire |
| $B_{i+1} = B_i - \beta_R R_i$ | DDS describing Blue force size in time period *i+1* |
| $R_{i+1} = R_i - \beta_B B_i$ | DDS describing Red force size in time period *i+1* |
| $\beta_B B_0^2 > \beta_R R_0^2$ | Blue wins if this inequality holds |

**Mixed Law (Blue uses aimed fire, Red uses area fire)**

| | |
|---|---|
| $\frac{\Delta B}{\Delta t} = -\alpha_R BR$ | Rate of change of Blue w.r.t time |
| $\frac{\Delta R}{\Delta t} = -\beta_B B$ | Rate of change of Red w.r.t. time |
| $B_{i+1} = B_i - \alpha_R B_i R_i$ | DDS describing Blue force size in time period *i+1* |
| $R_{i+1} = R_i - \beta_B B_i$ | DDS describing Red force size in time period *i+1* |
| $2\beta_B B_0 > \alpha_R R_0^2$ | Blue wins if this inequality holds |

**Transition Model (Blue changes from area to aimed fire, Red uses area fire)**

| | |
|---|---|
| $\frac{\Delta B}{\Delta t} = -\alpha_R BR$ | Rate of change of Blue w.r.t time |
| $\frac{\Delta R}{\Delta t} = -e^{-\phi i}\alpha_B RB - (1 - e^{-\phi i})\beta_B B$ | Rate of change of Red w.r.t. time |
| $B_{i+1} = B_i - \alpha_R B_i R_i$ | DDS describing Blue force size at time *i +1* |
| $R_{i+1} = R_i - e^{-\phi i}\alpha_B R_i B_i - (1 - e^{-\phi i})\beta_B B_i$ | DDS describing Red force size at time *i +1* |

### 3.1.5. Extended Transition Model

This model has the Blue force beginning the battle using area fire but transitioning to aimed fire as the battle progresses. The rate of this transition can be directly linked to Blue's success at conducting reconnaissance. By setting the transition rate to a function of characteristics of the reconnaissance system (both the platform and the sensors), as well as scenario characteristics, we model Blue success as a result of the reconnaissance system's capabilities in a scenario. In figure 3.1 we examine one possible construction of a transition rate function. Note that in this example, we have identified the following characteristics as contributing to the transition rate:

- Speed (SPD). This is a characteristic of the recon system platform and specifically is defined to be the distance it can travel per time unit
- Field of View (FOV). This is the measure, in degrees of the width of the line of sight fan of the recon system sensor.
- Maximum Detection Range (MDR). This establishes the maximum distance at which the sensor can detect an enemy force.

- Area of Interest (AOI). This is a diagonal measure of the area which is of tactical concern to the Blue force.

- Number of Blue Recon Systems (#SYS). This is the number of Blue recon systems that will be deployed for the recon mission.

- Number of Red Forces ($R_0$). The total number of Red forces at time zero.

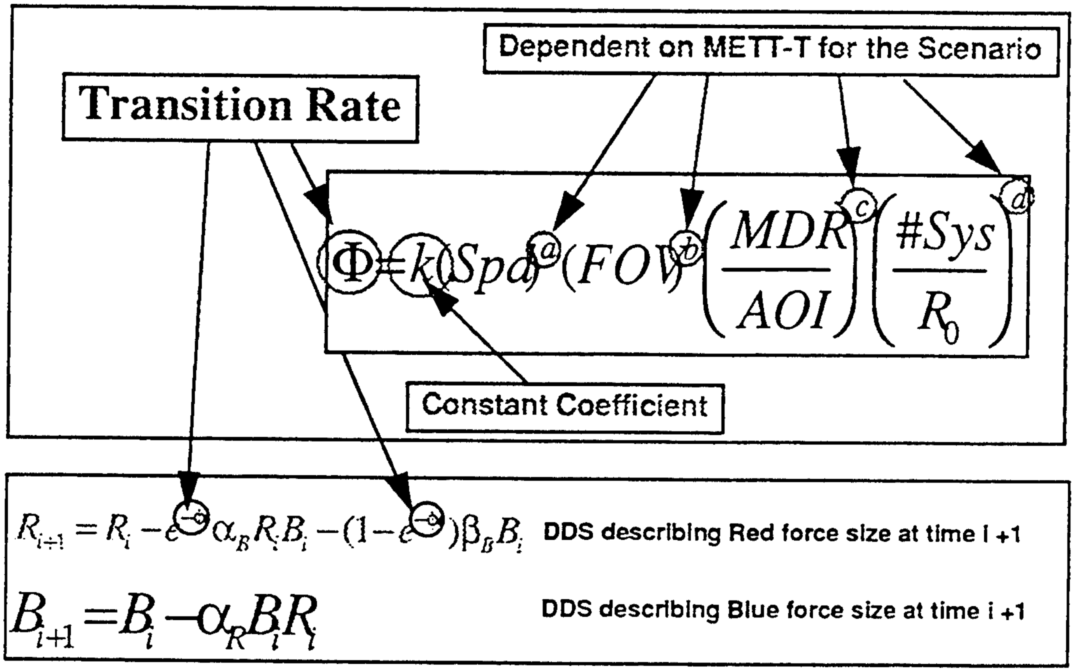


Figure 3.1. Transition Rate

As stated in the figure, the exponents *a,b,c,*and *d* as well as the constant *k* are dependent on the scenario's conditions (and can be weighted according to importance of the characteristics within a given scenario). The JANUS combat simulation tool would serve as a very good method to gather the empirical data needed to estimate the exponents in the transition rate equation.

### 3.1.6. Results and Future Work

Using the information above, battle scenarios have been developed to demonstrate the effects of reconnaissance. The Linear, Square, Mixed and Transition models are shown using a hypothetical list of parameters. In each instance, the winner, force sizes, force ratios, and the battle duration can be observed from a spreadsheet format (as shown in an example at Table 3.2.) or displayed graphically with an appropriate statistics package.

The spreadsheet format allows the user to quickly observe the impact of changing the input parameters when conducting sensitivity analysis and provides flexibility when examining parameter values obtained through computer simulation or historical archives.

Future work on the spreadsheet format includes experimentation with the transition rate equation to operationalize the Extended Transition Model and validation of the model through additional Janus simulation and study of U.S. Army historical archives at the Army Research Institute in Monterey, California (yielding parameter estimates to test model results for accuracy). Lead researcher in this area is Captain Mike Johnson whose Master's thesis will develop and extend the applications of Lanchester Laws in evaluating reconnaissance.

**Lanchester Equations**

| Parameters | | |
|---|---|---|
| Size of Blue forces | 100 | Bo |
| Size of Red Forces | 100 | Ro |
| Rate Blue attrites Red using AREA FIRE | 0.004 | alpha(1) |
| Rate Red attrites Blue using AREA FIRE | 0.003 | alpha(1) |
| Rate Blue attrites Red using AIMED FIRE | 0.65 | beta(1) |
| Rate Red attrites Blue using AIMED FIRE | 0.2 | beta(1) |
| Rate Blue transitions from AREA to AIMED FIRE | 0.2 | rho |

| Model | Winner | Time |
|---|---|---|
| Linear Law: | Red | 29 |
| Square Law: | Blue | 9 |
| Mixed Model: | Blue | 9 |
| Transition Model: | Blue | 16 |

**Linear Law**
AREA -vs- AREA
Winner: Red

| t | B | R | FR |
|---|---|---|---|
| 0 | 100 | 100 | 0.56 |
| 1 | 46 | 108 | 0.43 |
| 2 | 31.096 | 88.128 | 0.35 |
| 3 | 22.8747 | 77.1663 | 0.30 |
| 4 | 17.5792 | 70.1057 | 0.25 |
| 5 | 13.882 | 65.176 | 0.21 |
| 6 | 11.1677 | 61.5569 | 0.18 |
| 7 | 9.10535 | 58.8071 | 0.15 |
| 8 | 7.49898 | 56.6653 | 0.13 |
| 9 | 6.22418 | 54.9656 | 0.11 |
| 10 | 5.19783 | 53.5971 | 0.10 |
| 11 | 4.36207 | 52.4828 | 0.08 |
| 12 | 3.67527 | 51.567 | 0.07 |
| 13 | 3.1007 | 50.8089 | 0.06 |
| 14 | 2.63315 | 50.1775 | 0.05 |
| 15 | 2.23678 | 49.649 | 0.05 |
| 16 | 1.90362 | 49.2048 | 0.04 |
| 17 | 1.62262 | 48.8302 | 0.03 |
| 18 | 1.38492 | 48.5132 | 0.03 |
| 19 | 1.18336 | 48.2445 | 0.02 |
| 20 | 1.01209 | 48.0161 | 0.02 |
| 21 | 0.8663 | 47.8217 | 0.02 |
| 22 | 0.74201 | 47.656 | 0.02 |
| 23 | 0.63593 | 47.5146 | 0.01 |
| 24 | 0.54528 | 47.3937 | 0.01 |
| 25 | 0.46775 | 47.2903 | 0.01 |
| 26 | 0.40139 | 47.2019 | 0.01 |
| 27 | 0.34455 | 47.1261 | 0.01 |
| 28 | 0.29584 | 47.0611 | 0.01 |
| 29 | 0.25407 | 47.0054 | 0.01 |

**Square Law**
AIMED -vs- AIMED
Winner: Blue

| t | B | R | FR |
|---|---|---|---|
| 0 | 100 | 100 | 0.56 |
| 1 | 64 | 115 | 0.56 |
| 2 | 41 | 73.4 | 0.56 |
| 3 | 26.32 | 46.75 | 0.56 |
| 4 | 16.97 | 29.642 | 0.57 |
| 5 | 11.0416 | 18.6115 | 0.59 |
| 6 | 7.3193 | 11.4345 | 0.64 |
| 7 | 5.03241 | 6.67692 | 0.75 |
| 8 | 3.69702 | 3.40585 | 1.09 |
| 9 | 3.01506 | 1.00278 | 3.01 |

**Mixed Model**
AIMED -vs- AREA
Winner: Blue

| t | B | R | FR |
|---|---|---|---|
| 0 | 100 | 100 | 0.56 |
| 1 | 46 | 115 | 0.40 |
| 2 | 30.13 | 85.1 | 0.35 |
| 3 | 22.4378 | 65.5155 | 0.34 |
| 4 | 18.0277 | 50.9309 | 0.35 |
| 5 | 15.2732 | 39.2129 | 0.39 |
| 6 | 13.4765 | 29.2853 | 0.46 |
| 7 | 12.2925 | 20.5256 | 0.60 |
| 8 | 11.5350 | 12.5354 | 0.92 |
| 9 | 11.1018 | 5.0373 | 2.20 |

**Schaffer's Model**
TRANSITION -vs- AREA
Winner: Blue

| t | B | R | FR |
|---|---|---|---|
| 0 | 100 | 100 | 0.56 |
| 1 | 46 | 108 | 0.43 |
| 2 | 31.096 | 86.3102 | 0.36 |
| 3 | 23.0443 | 72.4503 | 0.32 |
| 4 | 18.0356 | 62.0269 | 0.29 |
| 5 | 14.6795 | 53.5607 | 0.27 |
| 6 | 12.3208 | 46.3722 | 0.27 |
| 7 | 10.6068 | 40.0875 | 0.26 |
| 8 | 9.33110 | 34.4739 | 0.27 |
| 9 | 8.36611 | 29.3734 | 0.28 |
| 10 | 7.62889 | 24.6718 | 0.31 |
| 11 | 7.08424 | 20.2822 | 0.35 |
| 12 | 6.6344 | 16.1358 | 0.41 |
| 13 | 6.31325 | 12.1758 | 0.52 |
| 14 | 6.08264 | 8.3541 | 0.73 |
| 15 | 5.9302 | 4.62844 | 1.28 |
| 16 | 5.84785 | 0.96026 | 6.09 |

Table 3.2. Spread-sheet Application of Lanchester Equations

## 3.2. Evaluating Reconnaissance: A Contingency Scenario with Competing Systems

We performed a study on reconnaissance using Janus (A). This effort resulted in a firm understanding of reconnaissance, a potential methodology to evaluate reconnaissance using Janus (A); and an understanding of the capabilities of two potential reconnaissance systems: a prototype UAV (utilizing an optical sensor) and a light RAH (utilizing the 2nd Generation FLIR sensor).

We initiated the study by researching four topics: reconnaissance usage and tactics, Armored force tactics, history of warfare in Bosnia-Hercegovina, and design methodology (Taguchi's Method). This knowledge was combined and utilized in a detailed study of reconnaissance in a contingency scenario in Bosnia-Hercegovina.

We studied the usefulness of two reconnaissance systems (RAH, and an UAV system), deployed versus a potential regional threat. The scenario examined an active defense against a harassment/attack on a hypothetical, U.S. held airfield outside Sarajevo. The recon systems were tasked to locate enemy concentrations (three possibilities existed), and provide information to support the commander's decision to assault the critical enemy mass. The design team utilized a three factor, two and three level, full factorial design to set up this experiment. The three factors were:

1. The Reconnaissance Platform (UAV or RAH)

2. The Commander's Preferences for Issuing Reconnaissance Orders (we used two commanders)

3. The Enemy Situation (each scenario employed one of three enemy dispositions with a well defined zone of concentrated enemy strength)

In the performance of the reconnaissance mission, data were collected for six effectiveness measures that the design team felt accurately reflected recon mission success and usefulness for this experiment.

These data revealed that the UAV system tested was more effective than the RAH system tested. However, the data also revealed potential concerns in our setup and inequities to be examined more carefully in later studies. These concerns were: air speed of the recon system, flying altitude of the recon system, visibility conditions over the area of operations, and interrelationships among the three factors not previously considered.

The group continued the study on reconnaissance by assisting the Operations Research Center, at the United States Military Academy, in a study of the potential usefulness of entropy as a measure of reconnaissance effectiveness. We were interested in correlating decreased states of entropy to the gain of useful information over time and increases in entropy to a lack of useful information concerning the enemy. The design team developed and implemented a data collection experiment for entropy calculations using Janus (A).

This experiment corrected previous concerns from the earlier experimentation to more equally compare the UAV and RAH systems. The data obtained included terrain and sensor affected visibility plots along the recon routes, and enemy detections versus time histograms for each recon system. Further, we calculated empirical probabilities of each recon system's chances to see each, unique, threat system over a ten minute standardized course. These data supported earlier conclusions that during daylight conditions in the terrain surrounding Sarajevo, the UAV system was a superior and more command useful recon system than the RAH system we tested.

In summary, we observed an interesting phenomenon in this setting that might explain the inability of the manned helicopter system (RAH) to outperform the unmanned system (UAV). We feel that the terrain in and around Sarajevo limits the effectiveness of the manned system. We observed that the average detection range was around one kilometer. At this short range, the optical sensing technologies are equal to or better than the FLIR sensing technologies. Without the possibility of greater detection ranges, the FLIR was unable perform to its potential.

Obviously, too, we should categorically state, that the capabilities and limitations of both the manned and unmanned reconnaissance systems are not completely represented or modeled in Janus (A). Performance parameters such as the timeliness or quality of information are not modeled as this information is transferred from receptor to decision maker. We agree that this information is degraded in this process to different degrees. We hope the manned system preserves the original state and quality of the information more thoroughly. This would give the manned system a performance edge not modeled in our experiment.

However, we feel both of these studies lend great insight not only in how to compare reconnaissance systems using computer simulation, but also in how to evaluate the absolute usefulness of reconnaissance using the Janus(A) simulation.

## 3.3. Using Entropy to Measure Recon Value: An Experiment in Alternative Measures of Effectiveness

In addition to an array of "traditional" information and information rate measures, such as "targets detected per minute," "time to locate 25% of enemy tanks," and "average range at detection," we have considered a few "unusual" measures that appear to have potential for the RECON problem. Of course, the traditional measures will continue to be heavily used in our proposed methodology, but there appears to be room for a few other measures. Following is a discussion of a candidate measure based on information theory.

### 3.3.1 Background

Entropy is a measure of "randomness" in a system, commonly used in information theory. If a system can be in any of n possible states, the entropy of the system can range between 0 (when the exact state of the system is known) to ln(n) (when the state of the system has maximal "randomness," which occurs when the state of the system is uniformly distributed over $n$ possible states). In general, if some information about the system is gained (in our case through RECON activities), the entropy will decrease. Thus, the rate of decrease of entropy (or measures such as the time required to decrease entropy by 50%, accumulated entropy decrease by milestone 3, etc.) might serve as a measure of RECON system mix performance. Such measures can be plotted as functions of time into the battle, in order to show how the systems perform over time.

Specifically, if a discrete system can be in state j with probability p(j); j=1,2,...,n, the entropy E of the system is defined to be $E = -\sum p(j)\ln(p(j))$, where the sum is over all states j for which p(j)>0. (For a continuous distribution, replace the sum by the corresponding integral. For example, if a single target is located on the real line in accordance with a Normal$(\mu,\sigma^2)$ distribution, the entropy of the target is a linear function of $\ln(\sigma^2)$.)

### 3.3.2. Bayes Updating

To use entropy decrease as a measure of information gain resulting from RECON activity, we suggest the following procedure:

a. Divide the region of interest into areas which might contain Red targets and which may be searched by Blue RECON;

b. Determine Blue's prior probability distribution representing the marginal distribution of location of each Red target, before RECON begins;

c. As RECON proceeds, consider it to take place as a sequence of searches in the designated areas;

d. When an area is searched, use Bayes' formula to update the current distribution of each target's location to obtain the posterior distributions for all targets;

e. Compute the decrease in entropy, for each Red target, resulting from the RECON report on the area just searched;

f. Accumulate and store the sum of entropy decreases of all Red targets, and the time of completion of the area search (this assumes the locations of the targets are independent);

g. Loop through steps (d) - (f) for the duration of the RECON battle;

h. Plot the composite entropy decrease as a function of time into the battle. The result is the "entropy trace," which gives an overview of the receipt of information over time, as the RECON battle was conducted.

i. (optional) Determine a "time value of information" for each target location, then compute a "time weighted information value" for the RECON battle. Another alternative is to weigh each target's entropy decrease by a factor representing the importance of the target, then sum the weighted values.

### 3.3.3. Computing the Entropy Trace in a Janus Experiment

To examine the use of entropy as a measure of reconnaissance value, we conducted a modest Janus experiment using ten runs with each of two RECON platforms, representing a RAH and a UAV. The experiment involved a Bosnian scenario developed by cadets Carroll, Glaser, and Mitchell at the Military Academy. These cadets carried out the experimentation, the data collection and data reduction using the ORCEN facilities at the Military Academy. Each simulated recon battle lasted ten minutes and involved a single RECON platform searching for 50 identifiable targets hidden among 400 500m X 500m squares, or "boxes." The RECON systems were able to search 261 of these boxes in each trial, following the preassigned routes in the scenario.

The entropy associated with each individual target was computed at times 0, 1, ..., 10 minutes, and the total entropy was calculated as the sum of the individual target entropy's. The following assumptions were made:

1. As far as Blue knows, each Red target could be placed in any of 400 boxes by Red. Actually, Red has placed all 50 targets in boxes that will be searched by Blue (i.e., somewhere within the set of boxes Blue will search during the RECON battle).

2. For Janus runs, the false alarm probability, $P_D$, is zero.

3. Target locations are independent, from Blue's point of view.

4. Each RECON system had detection probability at least 0.05 against each Red target.

For each individual target, the following comments hold:

5. Only 261 boxes will be searched by Blue during the RECON battle.

6. With false alarm probabilities equal to zero for each RECON system, entropy drops to zero when the target is detected and located (because the posterior distribution of the target's location then becomes a vector of the form (0,0,...,0,1,0,...,0)).

7. Starting entropy (at time zero) is ln(#boxes) = ln(400) = 5.99146, where it is assumed that Blue has no initial information about target location and thus the prior distribution is uniform over the 400 possible boxes involved.

8. The detection probability of a given RECON system against a given target is taken to be the relative frequency of detections in ten Janus runs with that system. If a given target was never detected in the ten runs, the detection probability was set equal to 0.05.

### 3.3.4. Data Analysis

Plots of the entropy values Blue achieved against the entire Red force in our Janus experiment (single platform vs. stationary/non-lethal targets) are shown in several figures as follow. It can be seen that the UAV system performed much better than the RAH for this particular terrain and scenario (see Figure 3.2.). The variation in entropy plots from run to run of the same scenario is indicated by the spread of the plots (entropy plots for all ten UAV runs made are shown in Figure 3.3. and highlight the variation observed due to the stochastic nature of detections, while plots of the standard deviations of entropy for the two systems are at Figure 3.4.). Plots of the change in entropy from time t-1 to time t ("deltas") are also shown below (see Figure 3.5.). These are the <u>entropy traces</u> for the two systems, as discussed earlier. The similarity in shapes of the entropy traces for the UAV and RAH indicates both systems were performing best around minutes 2 to 4, with another period of increasing performance near the end of the RECON battle. Note the entropy trace for the UAV is considerable higher than that for the RAH, indicating the UAV performed significantly better in this scenario at reducing entropy. All of these observations based on the entropy plots are in accord with results expected by the experimentation team, based on their knowledge of the scenario and RECON battles involved.

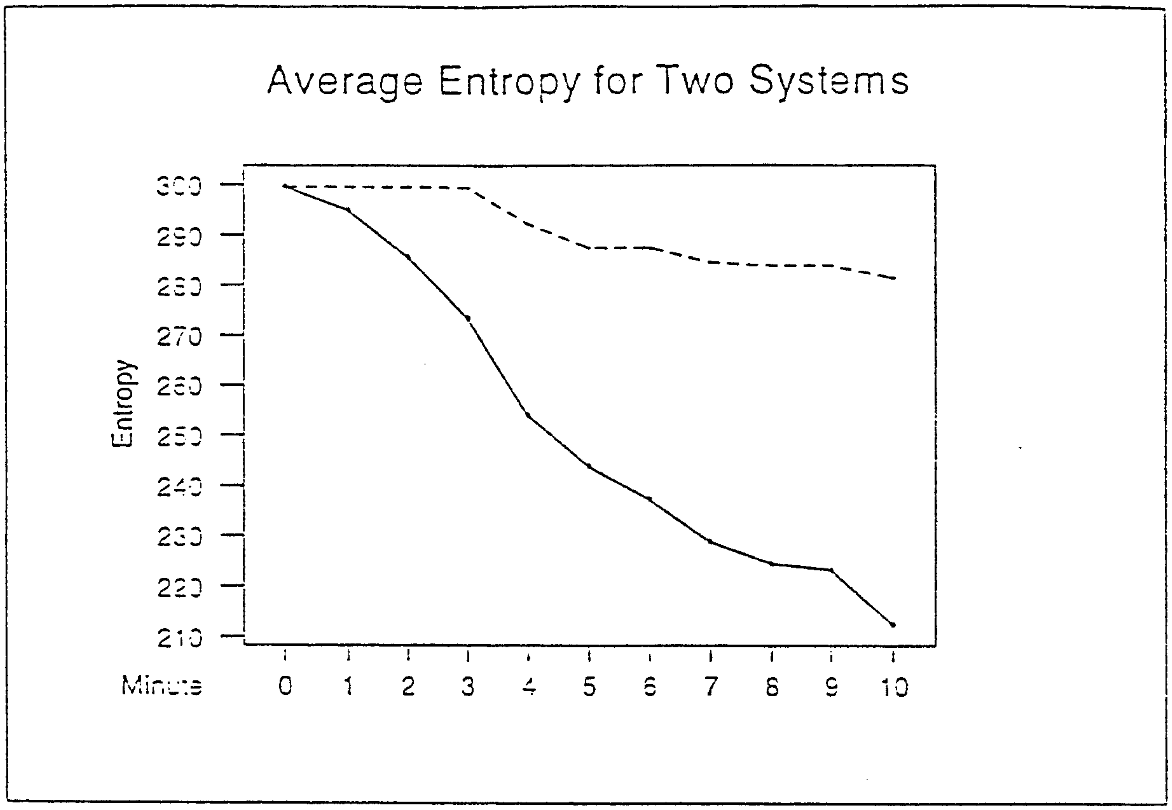


Figure 3.2. UAV (solid) and RAH (dotted) Entropy over a 10 Minute Battle.

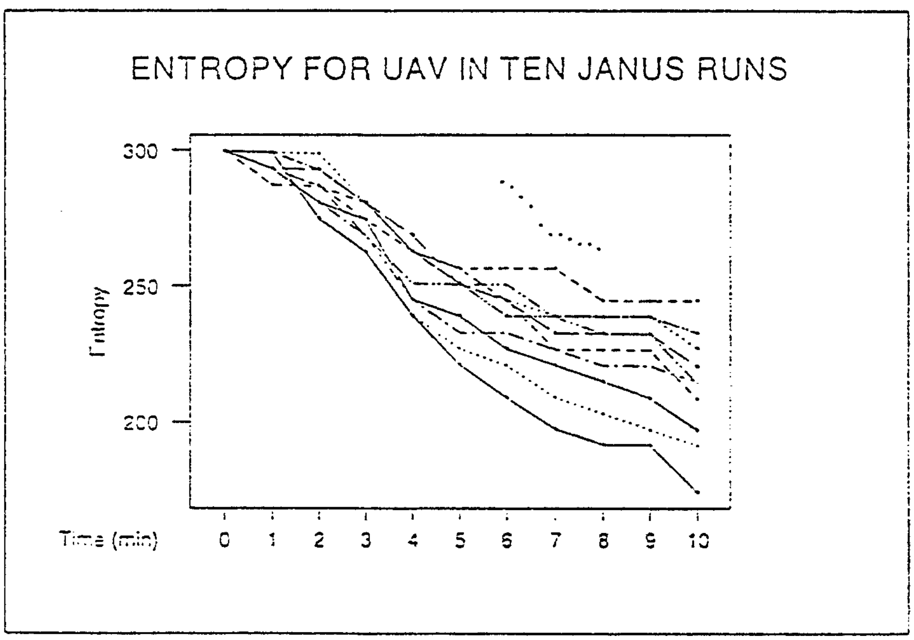


Figure 3.3. UAV Entropy Plots for 10 Runs.

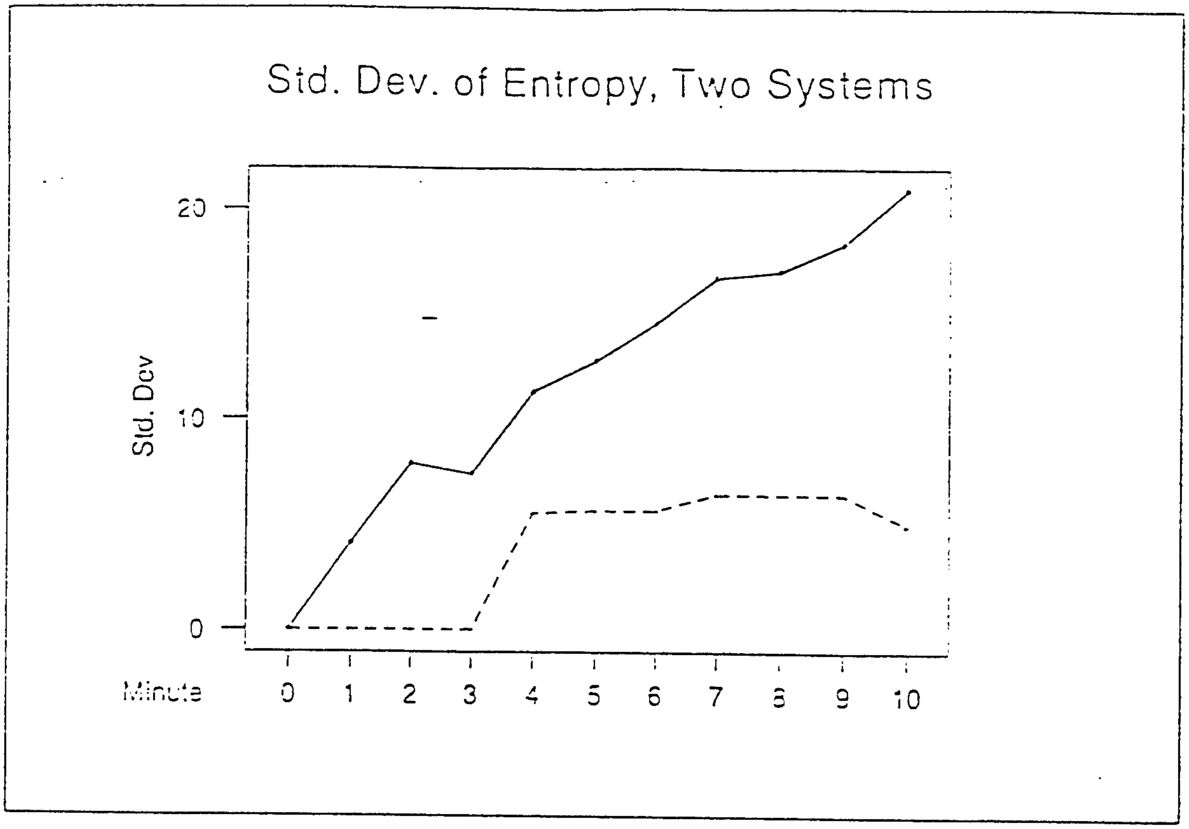


Figure 3.4. Standard Deviation for Entropy: UAV (solid) and RAH (dotted).

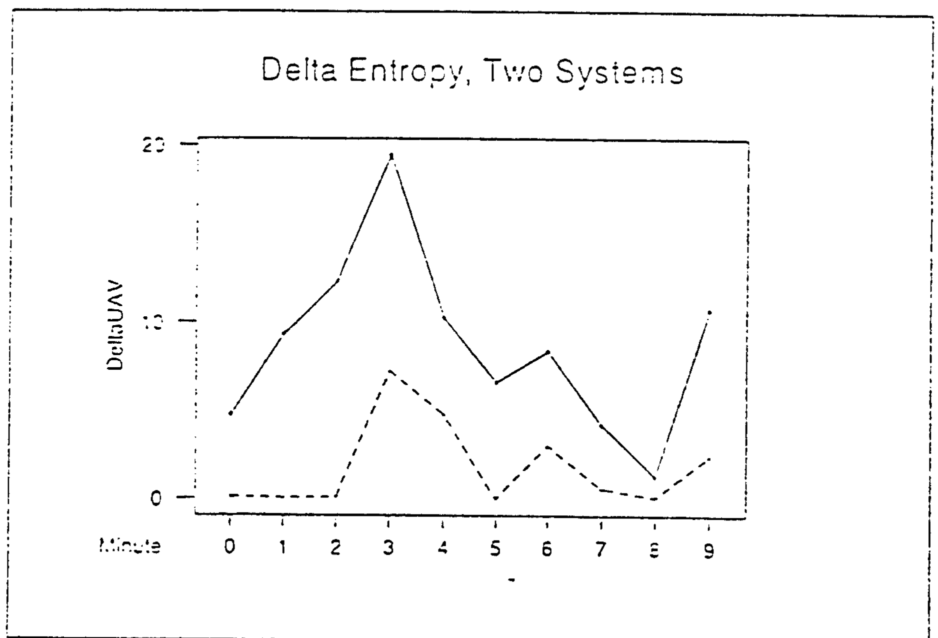


Figure 3.5. Changes in Entropy: UAV (solid) and RAH (dotted).

## 3.4. Extensions in Reconnaissance: A Study in Measures and Design

### 3.4.1. Experimental Design

The initial results from previous studies indicated that entropy might be a valid measure of recon effectiveness. This study was conducted to extend our research into entropy as an MOE of reconnaissance, examine the hunter/killer relationship (armed reconnaissance versus hunter/killer teams), and investigate other experimental design considerations.

We used the Bosnian terrain database as a hypothetical contingency based operation. The scenario is built on the premise that a U.S. peacekeeping force is landing at the Sarajevo airport. Serbian forces move to contain and interdict the U.S. landing. U.S. Army reconnaissance forces are ordered to find these forces (with priority on finding a battery of chemical munitions capable Serbian 220mm multiple rocket launchers and the Serbian command post) and engage with supporting 155mm and MLRS artillery. Two U.S. forces are examined in this scenario, based on a UAV or RAH equipped reconnaissance force. Specifics regarding the scenario and forces were as follows:

<u>Enemy Forces</u>: The Serbs consistently field the following forces; 6xT62 tanks and 12xBTR152 apc's divided into 2 stationary and 2 moving platoons, 3xBTR60 and 2xBMP Command Vehicles colocated to form the Serbian CP, 6x82mm and 3x120mm Mortars divided into 3 mortar platoons, 3x220mm MRC as the rocket battery, 12xInfantry Squads scattered at key terrain points to represent militia units, and 3xZSU23-4 divided to overwatch the CP, MRC battery, and a mech platoon.

<u>Friendly Forces</u>: The UAV force consisted of 5xStar Eagle unmanned, unarmed aerial vehicles with support from 2 sections (2xlaunchers each) of MLRS and 4 platoons (4 tubes each) of 155mmSP. The RAH force consisted of 7xRAH with 1xsection of MLRS and 2xplatoons of 155mmSP. The RAH was loaded out with 20mm HE, Hellfire Missles, and 2.75" rockets.

<u>Execution</u>: The UAV's flew at 100m altitude in a "racetrack" over the terrain at 100 knots. RAHs flew at 100 knots along terrain contours at 50m, stopping to pop up to 100m at selected locations on their paths. As enemy were detected, artillery was called for (see doctinal commander below), and in the case of the RAH, taken under direct fire.

<u>Doctinal Commander</u>: Artillery was called on detected enemy locations as follows:

- 1or 2 x155mm HE Volley against enemy infantry or mortars
- 2 x155mm Improved Conventional (IC) Volleys -vs- armored targets
- 1 x MLRS section strike -vs- the enemy CP or MRC battery

### 3.4.2. Results

The results from this study coincided with the results of the previous cadet examinations of the two reconnaissance systems. Using traditional measures, we see the UAV detected more targets than the RAH, however the RAH's ability to engage the enemy directly resulted in nearly the same casualties to the enemy. We expect this to highlight the usefulness of entropy as an MOE; destruction of enemy assets in a timely manner will also reduce entropy (permanent reduction of uncertainty--a target that is known to be destroyed no longer concerns a commander)! The measures of interest investigated here include the conventional measures of Average Detections, Average Kills, Total Detections, and Total Kills.

Average Detections: (See Figure 3.6) The UAVs moving at a constant 100 knots along a "racetrack" circling the areas of interest completed the reconnaissance mission much quicker than the terrain following RAH, as reflected in the average detections (over 10 runs each) graph above. This quicker response hints at a potential role for the UAV, as a dedicated hunter for artillery systems.

Average Kills: (See Figure 3.7) Due to its organic weapons, the RAH proved a much quicker killer. The UAV generated kills (from supporting artillery, and the MLRS especially) required a much longer lead time. Additionally, for deeper reconnaissance missions outside of effective artillery/MLRS range, the RAH would still retain some lethality, while the UAV would require Aviation support to inflict losses on the enemy (for example, if the enemy was equipped with FROG missiles, RAH would be ideal for finding and destroying this highly mobile target).

Total Detections: (See Figure 3.8) The UAV force consistently out-detected the RAH recon force. Flying at a higher altitude in rugged terrain with a wider field of view was in large part the basis for this disparity. Additionally, the 2d Generation FLIR equipped RAH may have suffered from false constraints in the way Janus physically models Thermal and Infared optics. We need to conduct more experiments on this subject, but it appeared that the thermal contrast/ambient temperature detection modifiers may be in error (often, a stationary, poped-up RAH would have an enemy system in clear LOS and fail to detect--a non-intuitive result).

Total Kills: (See Figure 3.9) In three of the runs, the RAH force was able to kill more of the enemy without considering the effects of artillery than the artillery support UAV. Likewise, in three other runs, the UAV force was able to kill more enemy than the RAH force, even when the RAHs were supported by artillery! The extreme variance seen in total kills is largely due to the chaos introduced into the simulation when a recon system is killed early in the battle. Even with 5xUAV or 7xRAH conducting reconnaissance, in some of the runs, one force or the other (or both) suffered heavy losses early in their mission. Intuitively, survivability is a prime requirement for a reconnaissance system and these results support that hypothesis. Life or death of a recon system can be the difference

between getting eyes on a high value target (such as an enemy Scud or Command Post) or first detecting the Scud as it is inbound!

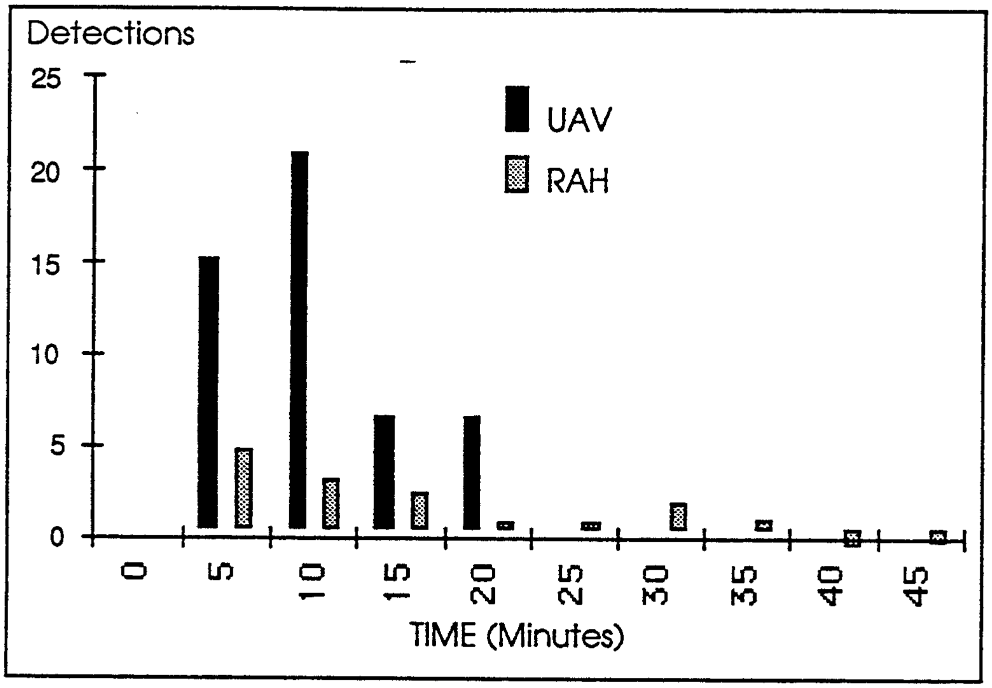


Figure 3.6. Average Detections Over Ten Runs by Time in Battle

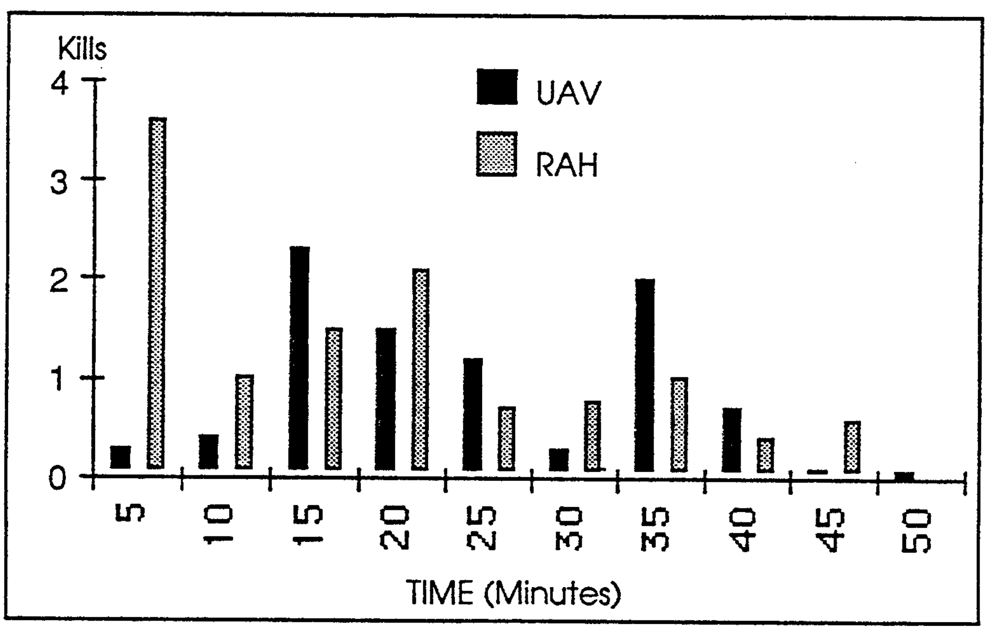


Figure 3.7. Average Kills Over Ten Runs By Time in Battle

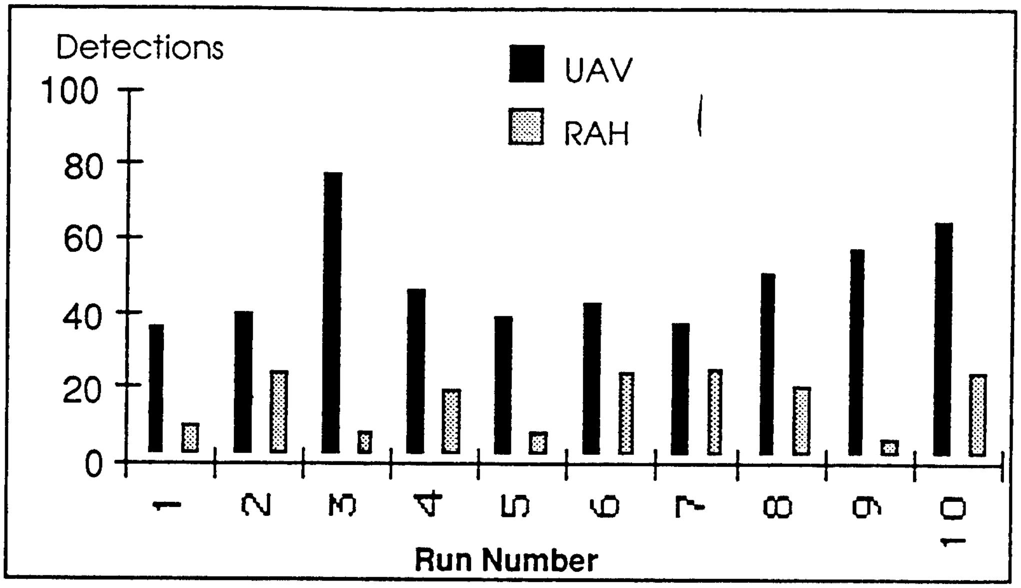


Figure 3.8. Total Detections for each Run

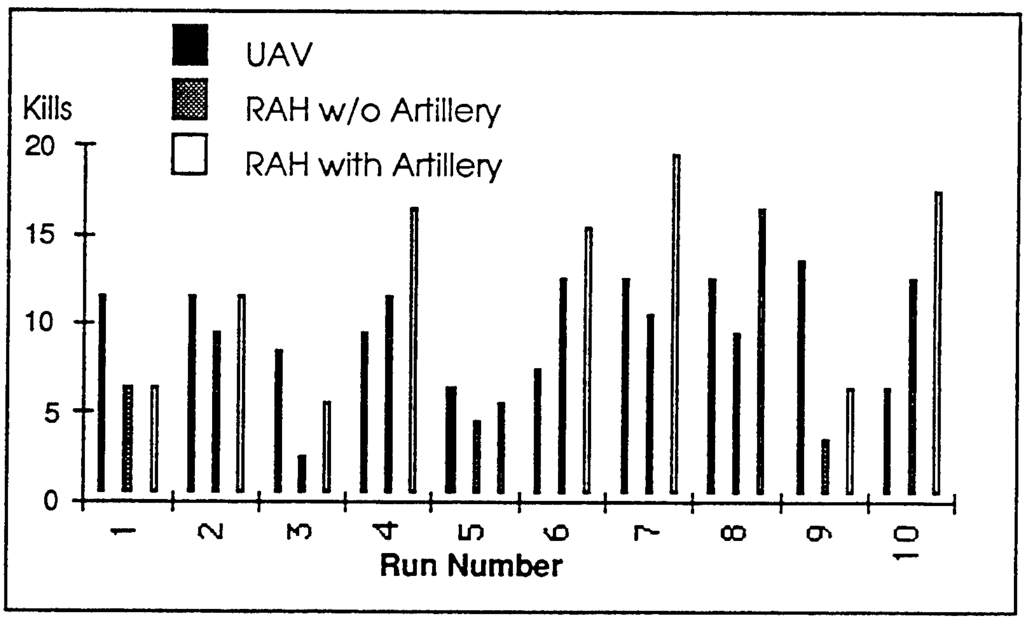


Figure 3.9. Total Kills for each Run

### 3.4.3. Future Work

Work on operationalizing entropy for this scenario (and Janus in general) will continue into 1994. Design and implementation of data probes and constructing an on-line entropy calculator is the thesis topic for a Naval Postgraduate School Master's student. Additional work will be done in this and other extension areas as advanced cadet project under direction of the USMA Department of Systems Engineering in conjunction with the ORCEN. Some of the concepts to be explored include:

- "Operationalize" Entropy. The previous experiments used hand input of raw detection and search data to compute entropy. Data probes designed to gather appropriate performance measures used to compute entropy, along with a user transparent computational aid to automate entropy calculations are required to make entropy a viable measure.

- Examine Entropy Extensions.

  - A Theater Ballistic Missile introduces more "uncertainty" into the battlefield than an infantry squad. Entropy should be capable of capturing this value (Hi/Lo Mix).

  - Multiple Systems. Entropy calculations are further complicated when multiple systems conduct reconnaissance.

  - Lethal/Non-lethal Recon Systems. Examine design considerations when comparing these types systems. In this case, killing power is provided by indirect fires only.

- Experimental Design Considerations.

  - Rules of Engagement. Constructive simulation of reconnaissance requires we play a "doctrinal" commander. In the JANUS (A) environment, there are several modelling techniques that will enable us to simulate the $C^2$ filter. For example, operating under UNIX, we can take "snapshots" of the battlefield at any time (black and white screen prints) and at any resolution (to model the granular effect of JSTARS or other systems).

  - What are appropriate measures of force effectiveness? This relates to linkage from system parameters into combat parameters.

# 4. Conclusions

Much work remains to be done to refine the individual steps of our proposed three step methodolgy.

Entropy appears to be a valid, useful measure of effectiveness for evaluating reconnaissance systems. However, software needs to be developed to automate the data collection of events effecting the level of uncertainty during a battle (target acquisition, identification, and destruction) as well as computational aids in conducting the Bayes updates required for calculation of Entropy values.

The Lanchester extended transition model appears to be a promising analytical model. We need to research historical data to develop appropiate values for the transition rate equation's exponent terms. Additionally, development of spreadsheet Macros will provide the analyst with a ready tool to conduct a first pass analysis of a reconnaissance system.

The studies conducted thus far tend to validate the three step methodology as proposed in this paper. The JANUS studies have confirmed the hypothesis that simple simulations fail to accurately model all of the effects of reconnaissance on a battle. The human commander and the decision making process have major effects on battle results (highlighting the need for a "complex simulation" possibly using AIRNET/SIMNET or other DIS tools such as the Battle Labs as the end of study vehicle to accurately quantify the value of reconnaissance). We also saw great value in the use of an analytical model (even a low resolution one, such as the one developed in Chapter 2 of this paper using performance ratings) to develop the simple simulation experiment, as well as the importance of using the simple simulation to refine both the analytical model and the experimental design prior to a complex, costly simulation involving DIS. The methodology also allows the analyst great flexibility when conducting a study. The analytical model, simple, and then complex simulation can all be conducted with tools available and appropriate to the system. Where available, the "man-in-the-loop" simulation could include observation of force-on-force exercises or data collection from a distributed interactive simulation. In any case, with proper planning these experiments can be conducted as a transparent overlay to training units, or as a data collection add-on to planned experiments conducted to augment operational tests.

The authors invite comments, questions, and suggestions from the analytical community (send to the Department of Systems Engineering, Operations Research Center, ATTN: Recon Project, USMA, West Point, NY, 10996). During FY 94 we intend to automate the Entropy measure and develop the Lanchester analytical model into usable form.

# 5. References


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# Appendix A. Briefing Slides

Enclosed are the briefing slides presented as an outbrief by CPT Strukel and Dr. Don Barr to MG Robinson, CG, Fort Rucker on 17 September 1993. Slides redundant with figures already presented in this paper have been omitted.

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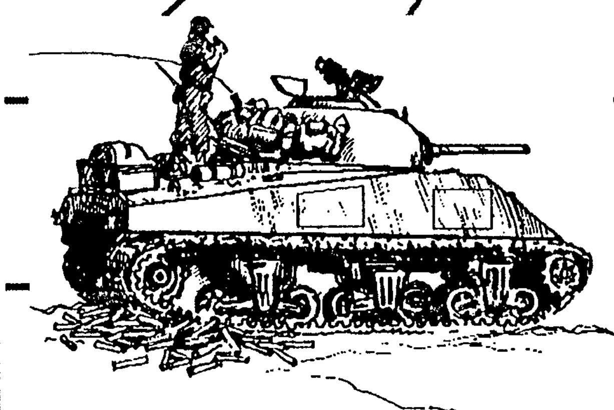
# Quantifying the Warfighting Value of Reconnaissance

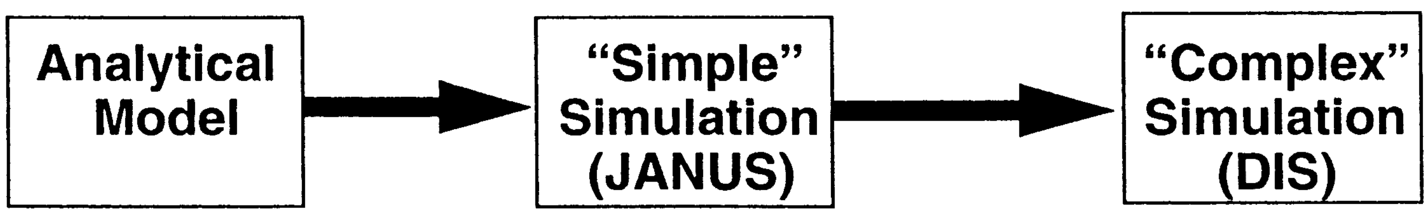


Reconnaissance Concept Briefing
MG Robinson
September 1993

# Intoduction

## What We Know So Far...

* We have DEFINED Reconnaissance.
* We have performed elementary mission/task analysis.
* We have developed a low resolution analytical model (examining system task performance)
* We have identified a potential methodology to quantify the war fighting value added of reconnaissance:

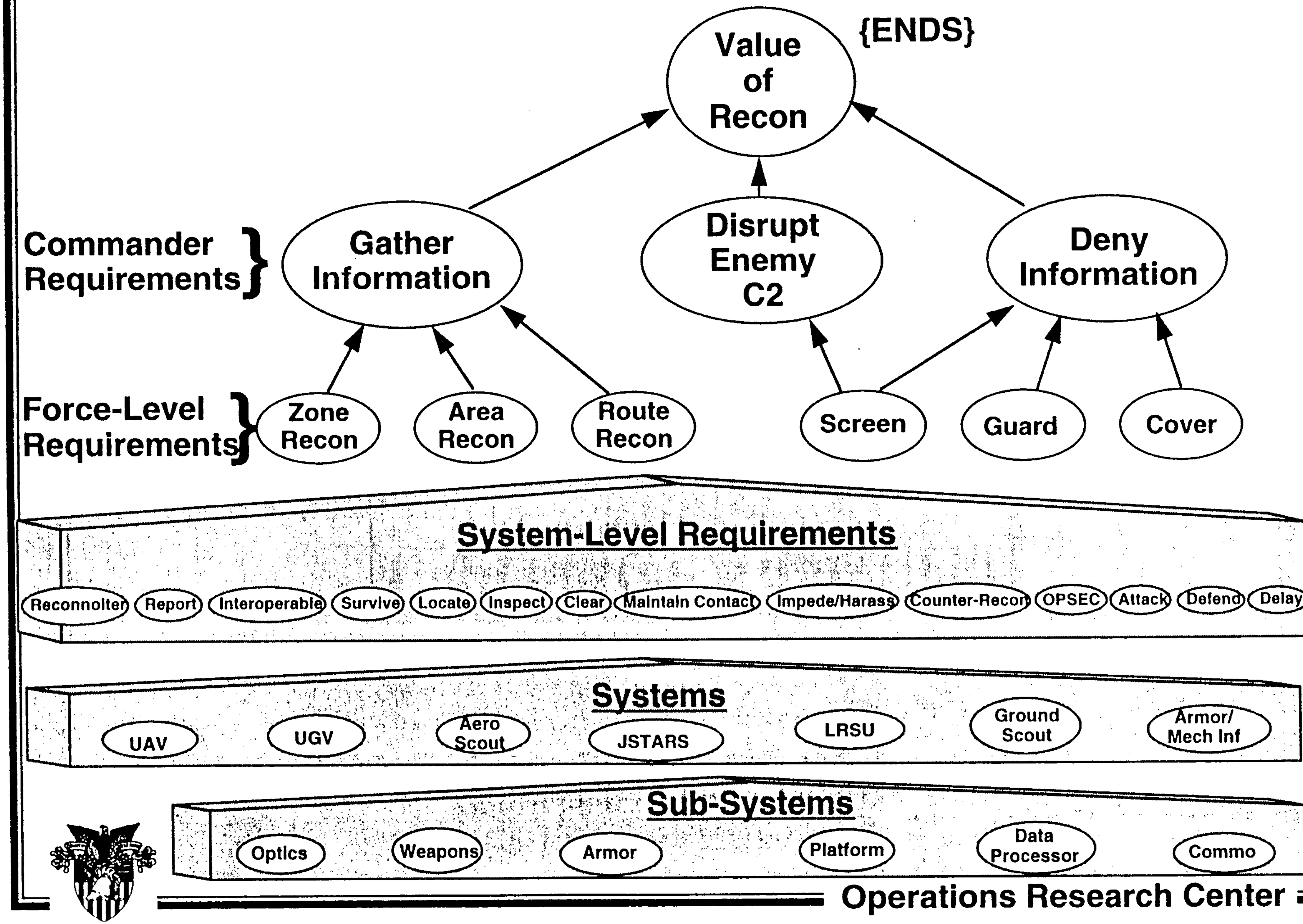


# Battle Process

| Phase I | Phase II | Phase III |
|---|---|---|
| Recon<br><br>"Gain Information" → | Command & Control<br><br>"Make Decisions" → | Fight<br><br>"Take Actions" |
| How does System impact on Information? | How does Information impact on Decision? | How does Decision impact on the Battle? |
| Model: What info is required? For a given scenario, what recon tasks must be performed and how often? | Model: How well does a recon system perform each required task? How many systems of each type do we need? | Model: How do the resulting decisions effect the battle outcome? |

The purpose of reconnaissance is to gain information in order to make decisions which give the best chance for success...

# Value of Reconnaissance

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United States Military Academy
West Point, New York 10996

# Lanchester Analytical Model

Captain Michael J. Johnson
Dr. Don Barr
Captain Steven E. Strukel
Naval Postgraduate School
Operations Research Center
Department of Systems Engineering
West Point, NY 10996
(914) 938-5672 (DSN: 688-5672)

# Lanchester Laws

| Lanchester Law | Model |
|---|---|
| Linear Law | Area fire -vs- Area fire |
| Square Law | Aimed fire -vs- Aimed fire |
| Mixed Law | Area fire -vs- Aimed fire |
| Shaffer's Model | Transition from Area to Aimed fire -vs- Area fire |

Blue force transitions from Area to Aimed fire as a result of reconnaissance:

* Transition Rate dependent on:
  - Reconnaissance System Parameters
    + Speed (Spd)
    + Field of View (FOV)
    + Maximum Detection Range (MDR)
  - Dimensions/Characteristics of the Battlefield
    + Area of Interest (AOI)
    + Number of Blue Recon Systems (# Sys)
  - Size/Composition of the Enemy Force
    + Number of Red Systems ($R_0$)

# Validation and Extensions

**Validation:**

* Lanchester Equations Proven
* Validate Recon Application Using:
  - JANUS(A) or other Simulation
  - Historical Databases (ARI, CALL, ...)

**Extensions:**

* Variable Transistion Rate over Time
* Integrate Lanchester Model with Entropy
* Red Transitions from Area to Aimed:
  - Models the Counter-Recon/Security Missions
  - More Accurate Model of Battle Process

Operations Research Center
United States Military Academy
West Point, New York 10996

# A Study of Reconnaissance in Janus Army

2LT Nicole Carroll
2LT William Glaser
2LT Webb Mitchell
CPT(P) Mark E. Tillman
Combat Simulation Laboratory
Department of Systems Engineering
West Point, NY 10996
(914) 938-5672 (DSN: 688-5672)

# Bottom Line

## 3 Cadets working as 1 design group in SE489.

## Scenario:

Humanitarian relief transitioning into conflict resolution in Bosnia-Hercegovina.

## Preliminary Analysis Results:

1. UAVs (optical sensing) equal or better than RAH-66 (2nd Generation FLIR sensing).
2. Terrain and visibility restrictions truncate and restrict Recon platform capabilities in this scenario.
3. Commander's decisions concerning use of recon assets affect platform's ability to formulate bigger picture.

## Follow-on Analysis:

1. Entropy Reduction Experiment with UAV and RAH-66
2. Degrade UAV based information with confusion and fog factors. Currently, information gathered with UAVs is as good as manned system's.

# Recon

## What the Cadets Did:

1. Reviewed and Studied Small Unit Tactics of US and Bosnian Forces.

2. Reviewed Previous Work Done by the Armor and Aviation Centers.

3. Reviewed and developed MOE for use in the measuring of recon and for use in the Taguchi Method.

4. Cut and Built Bosnian Terrain (first Bosnian terrain for Janus in the Army).

5. Built Appropriate Systems Needed (Terrain Markers).

6. Built and Rehearsed Appropriate Scenarios.

# Recon

## What the Cadets Did (continued):

7. Conducted First Experiment (a full factorial design with 3 factors).

8. Conducted Statistical Analysis of Experiment 1.

9. Developed Conclusions and Made Suggestions for Improving Scenario with Second Experiment (an entropy reduction proof-of-principle for the ORCEN).

10. Established a Methodolgy to Measure Entropy on Janus.

11. Built and Rehearsed Appropriate Scenarios.

12. Conducted Second Experiment and reported results.

# Alternatives

## Experimental Factors Used:

1) Recon System
   + level: UAV
   - level: Comanche

2) Commander
   + level: Cadet Nicole
   - level: Cadet Glaser

3) Scenario
   level 1: Enemy concentrated in area A
   level 2: Enemy concentrated in area B
   level 3: Enemy concentrated in area C

# Recon System Attributes

## UAV

1. Optical Sensing (2 TV cameras)
2. Flies at 100 knots
3. Flight Altitude of 100 m
4. Each scenario included two UAVs

## Comanche

1. Infra-red Sensing (2nd Gen FLIR)
2. Can fly at speed of 180 knots
3. Flight Altitude 10-50 m
4. Each scenario included two Comanches

# Detections on Janus

## Detection is a function of:

1. Line of Sight (can be over the horizon if sensor is capable, i.e. radars)
2. Acquisition Probability

## Acquisition Probability is a function of:

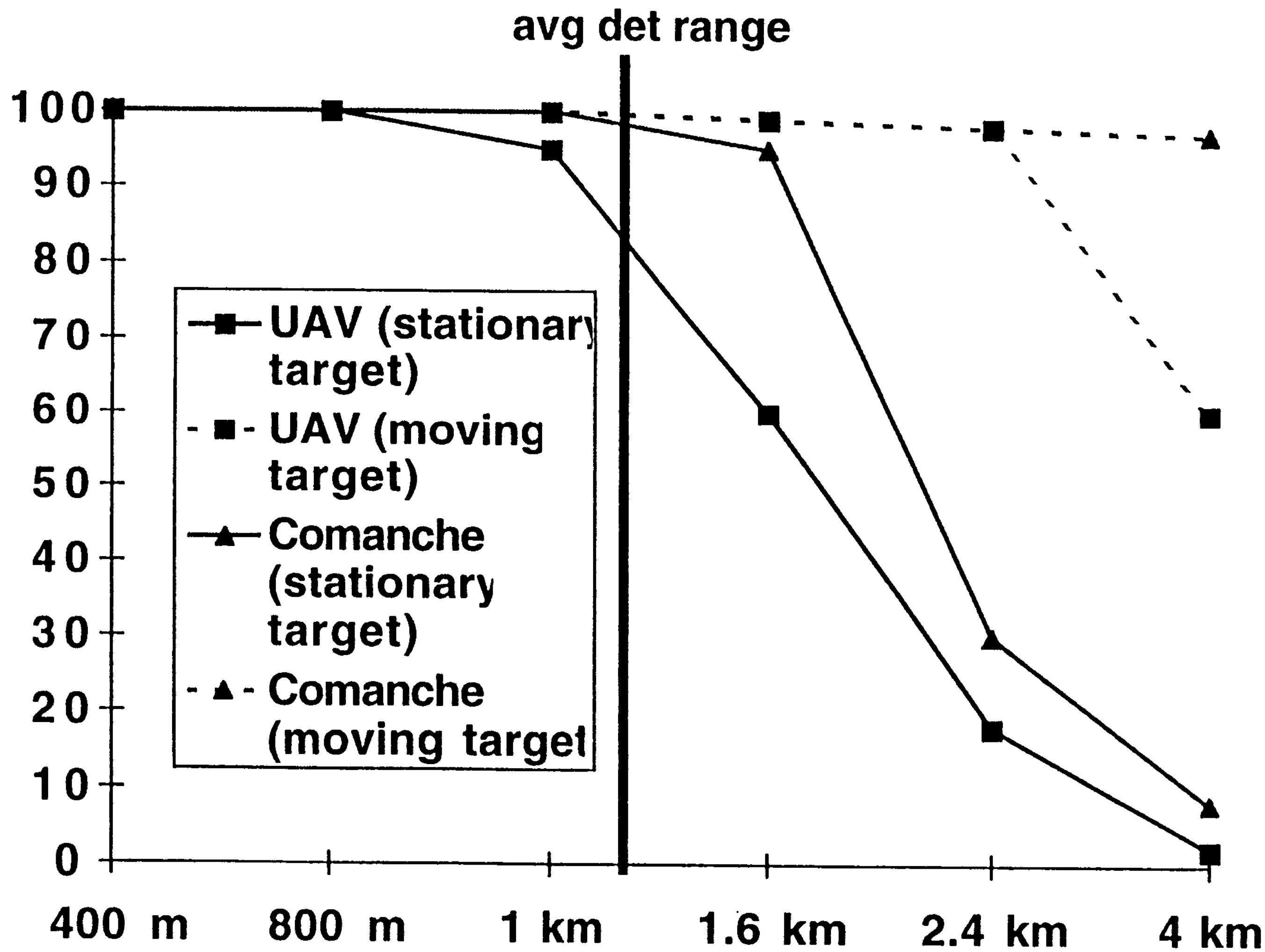
1. A minimum time for acquisition for the system
2. Sensor type
3. Target's contrast with background (optical and thermal)
4. Visible range to target
5. Size of target
6. Sensor's field of view (FOV)
7. Target's posture (moving or stationary, exposed or defl)
8. Whether the target has recently fired
9. Speed of sensor and target
10. MOPP status of system
11. Obscurants (optical length through smoke and dust)
12. Presence of blocking features (trees, bldgs, etc)
13. Minimum distance of 200 m, o/w p(acq)=1

# Sensor Attributes

| Sensor Attribute | UAV | | Comanche | |
|---|---|---|---|---|
| Number on System | 2 | | 2 | |
| Sensor Altitude | 100m | | 10-50m | |
| Type of Senso | TV cam | TV cam w/ zoom | 2G FLIR | Human |
| FOV | 10 deg | 7 deg | 3-30 deg | 20 deg |
| Max Detection Range<br>Where P(acq) of a T-80 tank >0.20 | .5km (s)<br>2.3km (m) | 1.9km (s)<br>4.4km (m) | 3km (s)<br>>10km (m) | .5km (s)<br>2.1km (m) |

Where:
(s) stationary target
(m) moving target

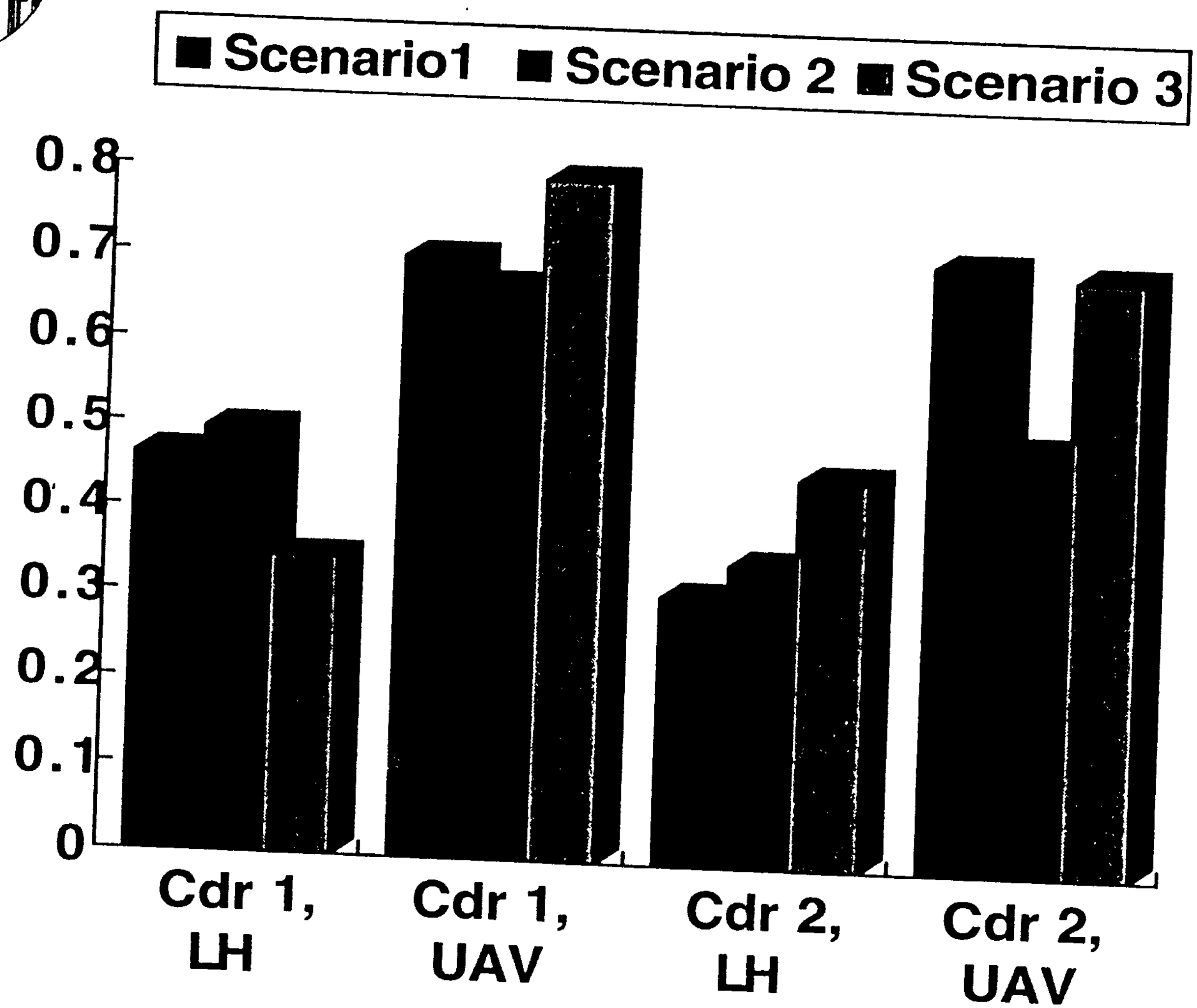
# Probability of Acquisition



# Measures of Effectiveness

1. Red losses
2. Blue losses
3. # of terrain/obstacle markers detected
4. Detection ratio
5. Average blue detection range
6. End game time

# Results


Scenario1
Scenario 2
Scenario 3
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cdr 1, LH
Cdr 1, UAV
Cdr 2, LH
Cdr 2, UAV

# What This Means

## Experimental Observations:

1. UAV more effective than Comanche in Bosnia. Optical sensors as effective as FLIRs at very close ranges (1 km).

2. The systems had equivalent survivability against Bosnian ground threat.

## Lessons Learned:

1. Inequities between systems (speed, altitude, etc) had greater than expected impact on Janus. This was validated in follow-on experiment.

2. Capabilities and limitations of both manned and unmanned systems are not completely represented in Janus(A).

Operations Research Center
United States Military Academy
West Point, New York 10996

# Using Entropy to Measure the Value of Recon

Doctor Donald Barr
CPT Steven E. Strukel
LTC James Armstrong
CPT Mark Tillman
Operations Research Center
Department of Systems Engineering
West Point, NY 10996
(914) 938-5672 (DSN: 688-5672)

# Experimental Design

## Experimental Factors Used:

1) Recon Systems
   + level: 1xUAV
   - level: 1xComanche

2) Preset search pattern using “doctrinal” flight path and profile

3) Scenario
   50 Red Targets (varying sizes and signatures) scattered over 400 “search boxes” in the AOI
   No blue or red firing (detections only)

# Results and Conclusions

* Entropy appears to be a valid measure of recon effectiveness:

  - In a *comparative* study such as this, does a good job of identifying relative reconnaissance value

  - Should perform equally well in a combat simulation--as enemy systems are destroyed, entropy will be reduced

* Work remains to *operationalize* Entropy

  - Computational Nightmare--need to automate both data collection and processing (data probes into JANUS and a spreadsheet (?) to update the Entopry values)

  - Need to refine observaton process--division of AOI into search boxes impractible (possible fix is use of an anlaytical model to calculate recon search "footprint"

Operations Research Center
United States Military Academy
West Point, New York 10996

# Extensions in Reconnaissance:
## A Study in Measures and Design

CPT Steven E. Strukel
Doctor Donald Barr
LTC James Armstrong
CPT Sue Romans
Operations Research Center
Department of Systems Engineering
West Point, NY 10996
(914) 938-5672 (DSN: 688-5672)

# Bottom Line

## Scenario:

Serbian forces attempt to contain and interdict a US Army forced insertion into the Sarajevo Airport. US forces respond with aerial recon supported by artillery.

## Preliminary Analysis Results:

1. UAVs (optical sensing) equal or better than RAH-66 (2nd Generation FLIR sensing) at detection rates and responsiveness (good “Hunter” when matched with effective “Killer” systems).
2. Terrain and visibility restrictions truncate and restrict Recon platform capabilities in this scenario.
3. RAH-66 provides greater flexibility in engaging discovered enemy. Independent Hunter/Killer, more responsive.

## Follow-on Analysis:

1. “Operationalize” Entropy (Data Probes and Post-Processor)
2. Experimental design considerations. Force size, structure, and variables.

# Experimental Design

## Experimental Factors Used:

1) Recon and Support Systems
   + level: 5xUAV + (4 Plt 155mm, 2 Sections MLRS)
   - level: 7xComanche + (2 Plt 155mm, 1 Sec MLRS)

2) "Doctrinal" Commander
   Artillery Rules of Engagement:
   - 1 Volley 155mm HE -vs- Inf/Mortar Squad
   - 2 Volley 155mm ICM -vs- Mech/Tank Target
   - 1 Volley MLRS -vs- High Value Target

3) Scenario
   Enemy Forces Constant at:
   - 2x Moving and 2x Stationary Mech Plts
   - 12x Inf and 9x Mortar Squads
   - 3x ZSU23-4 guarding a Command Platoon and a battery of 220mm MRLs (High Value Tgts)

# Conclusions

* Three step process appears to be valid
  - Interaction between JANUS-Analytical Model
  - Studies highlight need for “man-in-the-loop”
  - Analytical tool can be tailored to each study
* Work Remains:
  - Operationalize Entropy
  - Refine Lanchester Model (using historical data/ actual system parameters to define parameters and JANUS to refine the exponent/constant terms)
  - Experimental Design/Execution of a DIS Study

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| Director<br>Directorate of Combat Develpoments | ATTN: DCD<br>Ft. Leonardwood, MO | 1 |
| Mr. Mike Bauman<br>Director | TRADOC Analysis Command<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Assistant Deputy Chief of Staff<br>for Analysis | TRADOC<br>ATTN: ATAN<br>Ft. Monroe, VA 23561-5143 | 1 |
| Director<br>TRADC | ATTN: ATRC-TD<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SA<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SAA<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SAD<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SW<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SWL<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-SWH<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-F<br>Ft. Leavenworth, KS 66027-5200 | 1 |

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|---|---|---|
| Director<br>TRADC | ATTN: ATRC-FO<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-FM<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-FP<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-FS<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director<br>TRADC | ATTN: ATRC-FC<br>Ft. Leavenworth, KS 66027-5200 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-W<br>White Sands Missile Range, NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WS<br>White Sands Missile Range; NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WA<br>White Sands Missile Range, NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WB<br>White Sands Missile Range, NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WD<br>White Sands Missile Range, NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WE<br>White Sands Missile Range, NM 88002-5502 | 1 |
| Director | TRAC-WSMR<br>ATTN: ATRC-WL<br>White Sands Missile Range, NM 88002-5502 | 1 |

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|---|---|---|
| Commander | US Army Research Lab<br>ATTN: Advanced Concepts & Plans<br>White Sands Missle Range, NM 88002-5513 | 1 |
| Assistant Secretary of the Army<br>(Financial Analysis) | The Pentagon, Room 3E606<br>Washington, DC | 1 |
| Comptroller of the Army | The Pentagon, Room 3E588<br>Washington, DC | 1 |
| Honorable Walter Hollis<br>Deputy Under Secretury of the Army | (Operations Research)<br>The Pentagon, Room 2E<br>Washington, DC | 1 |
| Asst Sec Army<br>(Research, Development & Acquisition) | The Pentagon, Room 2E672<br>Washington, DC | 1 |
| Military Deputy to the ASA(RDA) | The Pentagon, Room 2E672<br>Washington, DC | 1 |